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Symbiotic Multi-Robot Fleets for Scalable Resilient Cyber Physical Systems

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Abstract

Humanity is currently facing challenges surrounding the operation, inspection and maintenance of current energy infrastructure and systems. These challenges include confined spaces, unstructured environments and hazardous areas to human health. Net-zero energy targets have instigated an accelerated energy transition, with the adoption of offshore wind farms due to increase, resulting in more and larger turbines. Several nuclear facilities are undergoing improvements in decommissioning to harness more information, improve site knowledge and create safer procedures. Robotics and autonomous systems are increasingly being used to address several of these problems within the energy sector. Currently, individual robotic platforms are being deployed in single, short term use cases in controlled environments with a team of engineers to evaluate the effectiveness of robotics for different use cases. This does not result in increased productivity, efficiency or value for operators of large facilities. This thesis focusses on the requirements of creating a Cyber Physical System (CPS) via a Symbiotic Multi-Robot Fleet (SMuRF) of diverse robotics and autonomous systems which operate individually or as part as a team to feed information back to a human-in-the-loop. A heterogeneous robotic fleet is used to leverage the robots capability within autonomous inspection missions where robots work as part of a team to complete the objectives of the mission. Symbiotic interactions occur autonomously across robotic platforms when elements of Cooperation, Collaboration or Corroboration (C^3) are required within the mission. This can be due to reliability or resilience issues which inhibit or limit the successful completion of a mission. The orchestration of the SMuRF is implemented via a Symbiotic Digital Architecture (SDA) that permits near to real-time C^3 for up to 1800 distributed robots, sensors and assets. This thesis demonstrates that the SDA enhances mission performance and intrinsic autonomy challenges in multi-robot fleet management to improve run-time safety compliance, reliability, resilience and productivity via real-world investigations with physical robotic platforms. The thesis envisions that the proposed SMuRF will assist in overcoming barriers in achieving scalable autonomy and directly benefit the objective of reducing cost, risk, and enhancing functionality to autonomous inspection, maintenance and repair operations.

Keywords: Aerial Robots, Cooperative Robots, Extreme Environments, Legged Robots, Robotic Fleet Management, Robot Teams, Robotic Manipulator and Wheeled Robots

Dedication

I dedicate this thesis to my family, Theresa, Mike and Niamh, who always lifted me up and been a true rock throughout this journey of both research and finding my feet. You all truly made this thesis possible. With all challenges and success, you stood by me and I have learned invaluable lessons that have shaped me to be the person I am today. I hope you can recognise that these are not my achievements alone; they are a testament to the foundations which you helped me build both professionally and personally. The sacrifices you have made when bringing me up have ensured I could stay resilient and stick to this journey to make you all proud. I dedicate this work to you all with immense appreciation and look forward to celebrating our shared success.

Passion, Action, Noble Intention Creates Progress

Consistently uphold your personal due diligence, accountability, and standards, while
simultaneously elevating and supporting those in your vicinity.

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I would like to greatly extend my gratitude to Prof. David Flynn for his invaluable guidance, unwavering support and expert mentorship throughout the course of this research. His insightful feedback, dedication and enthusiasm have been instrumental in shaping this work and developing my interpersonal skills. I am fortunate to have had his expertise and encouragement on this academic journey which is attributed to his commitment to reaching high standards of work in projects, holding each other accountable in our research and driving me to create my own opportunities with world class researchers. In gratitude, I extend my thanks for the recognition through awards and achievements we share, and for the invaluable support in fostering opportunities to pursue studies at these world-class institutions including the University of Glasgow and California Institute of Technology (Caltech). I thank him for identifying the potential (and for igniting the spark of drive to succeed ahead of my masters) when we first became colleagues and encouragment to take the step into completing the PhD, I wouldn't be who I am or where I am today if it wasn't for him.

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Author Declaration

The copyright in this thesis is owned by the author. Any quotation from the thesis or use of any of the information contained in it must acknowledge this thesis as the source of the quotation or information.

I declare that, except where explicict reference is made to the contribution of others, that this dissertation is the result of my own work and has not been submitted for any other degree at the University of Glasgow or any other institution.

Printed Name: Mr. Daniel Mitchell

Signature:

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Abbreviations

List of Publications as Primary Author

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1. Mitchell, D and Baniqued P et. al, Lessons Learned: Symbiotic Autonomous Robot Ecosystem for Nuclear Environments. IET Cyber-Syst. Robot. 2023. https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/csy2.12103. (Chapter 2.2, 4.2 and 7.3)

2. Mitchell, D et. al, Cover Image- Lessons Learned: Symbiotic Autonomous Robot Ecosystem for Nuclear Environments. IET Cyber-Syst. Robot, 5: i-i., 2023. https://doi.org/10.1049/csy2.12106, (Chapter 2.2, 4.2 and 7.3).

3. D. Mitchell, J. Blanche, S. Harper, T. Lim and D. Flynn, "Microwave Foresight Sensing for Safety Compliance in Autonomous Operations," 2023 IEEE International Conference on Omni-layer Intelligent Systems (COINS), Berlin, Germany, 2023, pp. 1-7, doi: 10.1109/COINS57856.2023.10189296, (Chapter 8).

4. D. Mitchell *et al.*, ‘A review: Challenges and opportunities for artificial intelligence and robotics in the offshore wind sector’, *Energy and AI*, vol. 8, p. 100146, May 2022, doi: 10.1016/J.EGYAI.2022.100146, (Chapter 2.1, 2.3, 3 and 4.1).

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List of Publications as Co-Author

§- *Indicates a reference in the main text where the author of this thesis is the co-author author of the published article.*

1. Baniqued, P.D.E.; Bremner, P.; Sandison, M.; Harper, S.; Agrawal, S.; Bolarinwa, J.; Blanche, J.; Jiang, Z.; Johnson, T.; Mitchell, D.; et al. Multimodal Immersive Digital Twin Platform for Cyber–Physical Robot Fleets in Nuclear Environments. *J Field Robot n/a*, doi: https://doi.org/10.1002/rob.22329, (Chapter 7.3).

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3. S. T. Harper, D. Mitchell, S. C. Nandakumar, J. Blanche, T. Lim and D. Flynn, "Addressing Non-Intervention Challenges via Resilient Robotics Utilizing a Digital Twin," 2023 IEEE International Conference on Omni-layer Intelligent Systems (COINS), Berlin, Germany, 2023, pp. 1-8, doi: 10.1109/COINS57856.2023.10189310, (Chapter 7.2).

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6. W. Tang, K. Brown, D. Mitchell, J. Blanche, and D. Flynn. 2023. "Subsea Power Cable Health Management Using Machine Learning Analysis of Low-Frequency Wide-Band Sonar Data" Energies 16, no. 17: 6172. https://doi.org/10.3390/en16176172.

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Evaluation of Structural Composite Materials," Journal of Composites Science, vol. 5, no. 12, p. 319, Dec. 2021, doi: 10.3390/jcs5120319, (Chapter 8).

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11. L. C. W. Kong, S. Harper, D. Mitchell, J. Blanche, T. Lim and D. Flynn, "Interactive Digital Twins Framework for Asset Management Through Internet," 2020 IEEE Global Conference on Artificial Intelligence and Internet of Things (GCAIoT), Dubai, United Arab Emirates, 2020, pp. 1-7, doi: 10.1109/GCAIoT51063.2020.9345890.

12. J. Blanche, D. Mitchell and D. Flynn, "Run-Time Analysis of Road Surface Conditions Using Non-Contact Microwave Sensing," 2020 IEEE Global Conference on Artificial Intelligence and Internet of Things (GCAIoT), Dubai, United Arab Emirates, 2020, pp. 1-6, doi: 10.1109/GCAIoT51063.2020.9345917.

13. Zaki, Osama Farouk, Flynn, David, Blanche, Jamie Rowland Douglas, Roe, Joshua Kenneth, Kong, Leo, Mitchell, Daniel, Lim, Theo, Harper, Sam Thomas, and Valentin Robu. "Self-Certification and Safety Compliance for Robotics Platforms." Paper presented at the Offshore Technology Conference, Houston, Texas, USA, May 2020. doi: https://doi.org/10.4043/30840-MS, (Chapter 7.1).

List of Awards and Significant Achievements

1. Cyber Physical Systems Rising Star 2024, Awarded by the Univeristy of Virginia, https://risingstars.linklab.virginia.edu/2024/participants/daniel-mitchell.html.

2. IET Rising Star 2023 at the IET Excellence and Innovation Awards, https://bit.ly/3QDaZyT, https://www.gla.ac.uk/schools/engineering/research/asc/researchthemes/smart-systems-group/news%20and%20events%20ssg/headline_1021983_en.html, 9 https://www.cms.caltech.edu/news-events/news/daniel-mitchell-receives-iet-rising-star-award.

3. University of Glasgow Images of Impact Competition – Future Impact Runner up 2023 – A scalable Symbiotic Multi-Robot Fleet for Offshore Renewable Energy.

4. Peoples Choice Award Visualise your Thesis Competition 2022- Symbiotic Multi Robot Fleet Autonomy, https://youtu.be/weSZjT3H-BA?si=NifubOFsZor2OQDI.

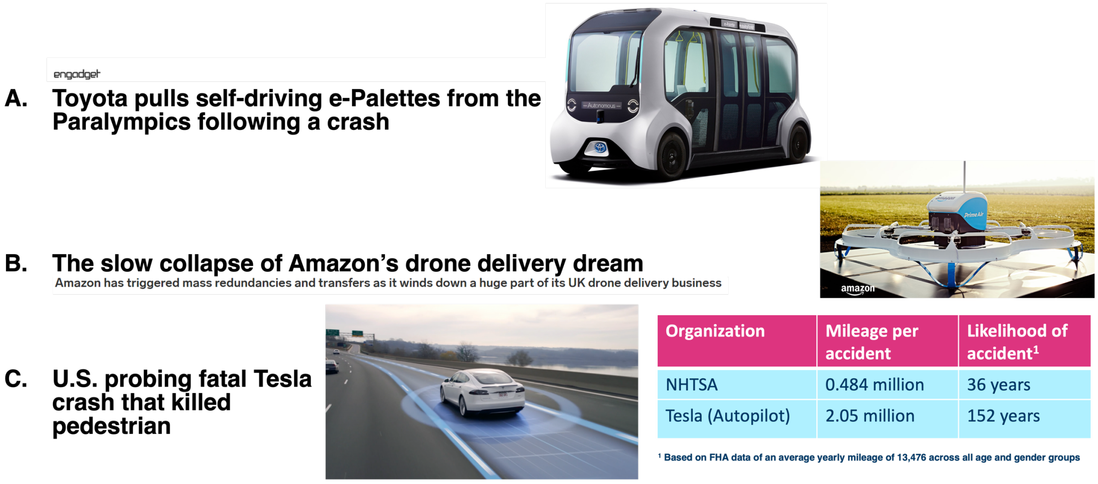
5. Winner of the Postgraduate 1st Year Research Prize for 2021 from the Institute of Sensors, Signals and Systems, Heriot-Watt University, https://smartsystems.hw.ac.uk/isss-postgraduate-research-prize-for-2021/.

Keywords and Definitions

Keyword	**Definition**
Cyber Physical System	A complex system with natural integration and comprehensive collaboration of computation, communications and control technology often connected via cyber assets in the digital world and physical assets in the real world.
Cybersecurity	Referring to the process of protecting the components of a cyber physical system from an attack (can be physically or digitally) to prevent unauthorised access to personal or sensitive infrmation or theft and damage.
Digital Twin	A digitalised copy of a physical asset, environment and/or system that is connected to the physical asset and operational data is shared to the digital copy.
Foresight	A robot with the ability to increase the situational awareness of visible and non-visible threats to supplement existing sensing capabilities, which are currently limited to line of sight.
Reliability	The act of monitoring and ensuring the operations of onboard systems including mechanical parts, components, electronics, software and onboard sensors with the aim to reduce risk of failure and maximise the health of the robotic asset lifecycle, hereby, increasing the mean time to failure.
Resilience	The ability for a system to recover from or adjust to misfortune or unforeseen circumstances. With the perspective of safety compliance and robustness where resilience enables a robot to survive and remain operational irrespective of adversity, maximising the rate of mission success.
Symbiotic Multi-Robot Fleet	A group of diverse robots which differ in type and application however, as a team leverage the capability of an inspection, maintenance and repair mission.
Symbiotic System of Systems Approach	Reflects the lifecycle learning with knowledge exchange for mutual gain across systems where symbiosis encourages bidirectional knowledge exchange.

1. Introduction

Robotic platforms are increasingly being deployed with the aim of achieving regular autonomous Inspection, Maintenance and Repair (IMR). However, these types of deployments exist under limited mission profiles and conditions including single use case, short term deployments within controlled ambient environments. Large companies with the resources to accelerate at scale have utilised product-centric mindsets which has seen several autonomous systems fail as presented in Figure 1-1. These examples have been attributed to human error, unknowns or product faults where issues lie within resilience, reliability and safety. In Figure 1-1A, Toyota faced a human-in-the-loop or software error resulting in the injury of a Paralympian whilst the system was under manual control. In B, Amazon have been trying to develop their Beyond Visual Line Of Sight (BVLOS) delivery where in 2013, Jeff Bezoz first presented 30 minute deliveries via drone however, this is expected to be common by 2030 in the UK [1–3]. There have also been several cases where autonomous vehicles have crashed with pedestrians and emergancy vehicles on separate occassions as displayed in C [4–6]. Within the latest failures, they mostly relate to human errors, where autonomous systems need to manage with people and dynamic situations. However, with respect to more controlled environments such as freeways where variables are minimized, data from Tesla indicates that autonomous vehicles are safer than normal, human driven cars compared to data from the National Highway Traffic Safety Administration (NHTSA). This is represented by the decreased likelihood of an accident presented in the table within Figure 1-1. This data poses a significant question. How safe is safe enough? This is widely seen in healthcare from aspirin to covid vaccines where there is a level of accepted risk [7,8].


engadget

A. **Toyota pulls self-driving e-Palettes from the Paralympics following a crash**

B. **The slow collapse of Amazon's drone delivery dream**

Amazon has triggered mass redundancies and transfers as it winds down a huge part of its UK drone delivery business

C. **U.S. probing fatal Tesla crash that killed pedestrian**

Organization	Mileage per accident	Likelihood of accident[1]
NHTSA	0.484 million	36 years
Tesla (Autopilot)	2.05 million	152 years

[1] Based on FHA data of an average yearly mileage of 13,476 across all age and gender groups

Figure 1-1. Key headlines highlighting failed autonomous systems deployed within the field from Toyota, Amazon and Tesla [4–6].

Over the years, the capabilities of individual platforms have improved significantly to access more areas, operate at higher speeds and with improved manipulation, sensing payloads and battery endurance. To date, this has enabled robots to reach a position where they can add significant value for operators within a myriad of sectors, hence short-term deployments in the field are being considered. However, as robots are deployed beyond short term durations/demonstrations challenges exist in the autonomy regularly overcoming the harsh environment and unstructured environments [9,10]†.

To date, development of robotic platforms have improved in the ground-up capability to address these challenges where tracked, legged, wheeled robots have been used within short based investigations to assess their suitability for inspection missions. Ground-up challenges addressed include improving areas such as overcoming obstacles like stairs, achieving ATEX compliance in explosive environments and improving sensor payloads for inspection. In addition to validating tests on gravel pads, ramps, narrow passageways, confined spaces, grated flooring and then on the live offshore facility. Several offshore companies such as Equinor, Total Energy, British Petroleum and Petronas have utilised their offshore sites as testing environments for these robots such as Taurob (an ATEX compliant tracked robot) environments [11–13], SPOT quadruped (Legged robot developed by Boston Dynamics) [14,15], and Anymal C quadruped (Legged robot developed by Anybotics) [16,17]. Robots also improve recording of inspection results as the autonomous system can save results as data which can be assessed later, whereas, human error can take place during note taking and manual labour when fatigued [18,19].

Within the current state-of-the-art, there are issues surrounding resilience, reliability and safety of robots and autonomous systems. The previously discussed robotic platforms all require a human engineer to teleoperate or assign autonomous missions for the robot to complete. When the robot faces challenges which the programming or software is unable to overcome, the human is required to assist via physical in-person intervention or reprogramming. To ensure safety of both robot and personnel, this hereby requires 2-3 personnel per robot in deployment (A human is required for each of these tasks: programming, fixing the robot when it fails and to oversee safety). Therefore, in recognition of this problem faced when autonomy fails, a robotic non-intervention challenge exists around resilience, reliability and safety which are the key themes throughout this thesis.

Often in robotics, it is assumed that the robotic hardware is the reason for a failure in a robot or autonomous mission. However, often it is the Artificial Intelligence (AI) that is unable to comprehend a situation or task which a robotic platform has to complete or overcome. Autonomy can be considered as a characteristic of a system which commonly uses AI to determine a course of action via autonomous decision making. Autonomy can be represented via different levels as presented by Mitchell *et al.* [20]†, and may be used to ensure safe operation of the autonomy as the variables, conditions or environment becomes more complex. For example, a self-driving car may be permitted to drive fully autonomously on a motorway however, not permitted in the city, as within the city there are more complex entities present such as humans. AI can be considered as technology or software which enables for a system to think or act in a certain way. This can enable a robot to decide the most optimum path to take [21], operate safely in a shared environment with a human [22] or designate tasks to other robots [23].

Robots must become resilient and reliable to be coordinated by a Human-In-The-Loop (HITL) but also overcome these challenges to reduce human intervention in these environments. When robots fail, they become an additional operational overhead and burden within a facility, therefore this must be minimised as effectively as possible to minimise the redeployment of personnel.

As discussed previously a current focus is on the ground-up capabilities of robots such as ground, tracked, aerial, subsea robots, however, this will result in a bottle neck for robots if different approaches are omitted from consideration. The capabilities of robots do need to improve and will always face challenges in improving battery life, agility, sensing payloads and situational awareness, however, for facility operators we need to shift this focus to balance between a top-down and ground-up capabilities. This allows for improved coordination and the ability to deploy robots in a timely, efficient manner that is scalable and delivers value for operators. This facilitates diverse operation of a wide range of robots and IMR activities.

When taking a top-down view forward, there are challenges faced which include safety compliance, reliability, productivity and resilience. Robotics should always operate efficiently, however, safety compliance should always take precedence. This should be observed in all areas where some examples include confined spaces and the presence of humans or in dangerous scenarios which may cause harm to themselves and/or other valuable equipment. Reliability includes the ability for a robot to self-certify its own systems. Are the motors operating within designed thresholds? Are programs operating as intended? These should all be confirmed during teleoperation and autonomous operations. Resilience can be mission specific depending on the sector however, can be summarised briefly as the ability for a robot to overcome obstacles or operational challenges which may lead to mission failure. To overcome these challenges, this could include scenarios where robots help each other out through fleet management or coordination via a HITL to overcome challenges.

1.1. Main Objective and Aims

The motivation of this thesis seeks to address challenges which currently exist across academia and industry with the aim of achieving scalable and Symbiotic Multi-Robot Fleet (SMuRF) via a cyber physical systems approach as visualised in Figure 1-2 for the Offshore Renewable Energy (ORE) sector. The first element of this thesis seeks to address Multi-Robot (MR) fleet management. As identified above earlier, single robot deployments require at least three personnel to deploy a robot in short term semi-autonomous missions. For value to be created for facility operators, a reduction in the number of personnel required per robot must take place, which requires advanced autonomy to overcome regular issues which mean robots are unable to overcome challeges. This thesis identifies that roles will change and develop as more robots are increased within a facility such as jobs as systems engineers where the responsibility is held in fleet management within robot task allocation and maintenance of robots. This will become increasingly important as more robots and robot types are introduced within different operational facilities. Therefore, to create operationally optimised systems, a significant reduction in the number of human interventions is required to establish value for facility operators. Secondly, resilience and reliability concerns will be addressed leading to improvements in long-term autonomy in hazardous environments. Robots must be able to overcome and adapt to unforeseen challenges which inhibit mission completion. This is mainly attributed to the improvement of AI algorithms within autonomous systems resulting in resilience challenges for robotic systems, however, is linked to the non-intervention challenges as a robot must overcome challenges itself, realise that it requires remote human assistance to overcome a challenge and lastly, decide when a human must attend the mission space to overcome the challenge. An additional point is that in some cases, such as radioactive nuclear environments, it may be that a human is unable to assist on site and therefore remote assistance via remote operation may be substantial to assess the best options to overcome the challenges. Thirdly, symbiosis across systems where robots can leverage the capabilities of the inspection across the fleet to improve efficiency and effectivness of overall operations as a heterogeneous fleet. The key reasons for this is due to robots being designed to complete different jobs, some robots are also designed to take slightly different approaches to similar tasks. Therefore, it is advantageous where robots can symbiotically help each other to corroborate inspections around a facility

In addition, to complement the inspections which robots are required to undertake, a dual purpose non-contact, non-destructive radar sensor was used for the purposes of asset integrity inspection, the radar sensor was utilised to inspect surface and subsurface materials for fault precursors to enable remedial action to be taken earlier and prevent the downtime of assets. This was applied to, composite wind turbine blades iron rebar within civil infrastrcuture and overhead line sag in detail in Chapter 8. Secondly the same sensor was used to provide foresight in autonomous missions, ensuring resilience in high consequence environments and to provide new inights in asset health monitoring for surface and subsuface defects which may exist in infrastructure. Foresight sensing enables a robot to increase the situational awareness of visible and non-visible threats to supplement existing sensing capabilities which are currently limited to line of sight. Examples include sensing beyond

Figure 1-2 Composite image of a SMuRF utilised for inspection on an offshore wind farm using commercial-off-the-shelf autonomous systems and sensors. Clockwise from top centre- Offshore wind turbine, C-Worker 7 autonomous surface vessel, DJI Tello, Boston Dynamics SPOT, Limpet Sensor, Dual UR5 Clearpath Husky and Intel Falcon 8+.

visual line-of-sight of a doorway or through fog, smoke or steam which has limitations for standard sensors on robots currently.

1.2. Outline of Thesis

In this segment, the thesis structure will be detailed, chapter-by-chapter, offering the reader insight into the research evolution - from the initial concept to the conclusion of the study - and its subsequent application to the final vision of symbiotic multi-robot fleet autonomy with a real-world deployment of a team of heterogenous robots. Chapter progression and key contributions are displayed in Figure 1-3.

Chapter 1 offers a succinct overview of the primary challenges addressed in this thesis, presenting the central objective and goals of this research. It provides introductions to key contributions, accompanied by a summary of the chapter main points.

Chapter 2 systematically outlines the market trends that are leading to an increase of mobile service robots conducting inspection, maintenance and repair activities for both the offshore renewable energy and nuclear sectors. The chapter firstly introduces the upscaling of the offshore renewable energy sector in the United Kingdom (UK) and then presents the primary support functions and lifecycle in design, construction and end-of-life of an offshore wind farm. The nuclear sector is then presented where similar support functions include: maintenance, normal operation, storage of nuclear waste, monitoring nuclear waste, emergency radiation monitoring and radiation hardening/tolerance for hardware. The key trends in the broad robotics market is presented alongside the academic database trends which highlight areas which academia are focused on currently related to the energy sectors previously discussed. Finally a chapter summary is presented.

Chapter 3 provides an in-depth exploration of foundational topics crucial to the understanding of the research context within this thesis. The chapter presents background literature on cyber-physical systems, safety considerations, cybersecurity aspects, standardisation efforts, and the comparative analysis of top-down versus ground-up approaches in robotics which is of particular importance for the reader. This chapter lays a comprehensive groundwork by delving into key theoretical underpinnings hereby setting the stage for subsequent empirical investigations and analyses.

Chapter 4 conducts a comprehensive literature review, presenting the current state-of-the-art related to individual mobile service robots, multi-robot teams and cyber physical systems. The initial subsection focuses on evaluating the ground-up capabilities of prominent industrial and academic robots to date. It begins by defining levels of autonomy, addressing common misconceptions within the field regarding operational autonomy. Subsequently, the discussion delves into the ground-up capabilities for field robotics for industrial applications and within academia, considering their respective hype cycles and projecting potential advancements based on robot types. An examination of the DARPA Subterranean challenge follows, representing the pinnacle of achievement in multi-robot fleets to date (Review conducted December 2023). A thorough critical analysis of the robotic teams involved in this competition is presented. The exploration extends to cyber physical human systems, incorporating bibliometric analysis and an examination of key sectors contributing to this evolving field. The section concludes with a summary encapsulating the key findings and insights.

Chapter 5 presents the key contributions with respect to the main objectives of this thesis. This includes symbiosis which is inspired from nature where key examples and concept such as mutualism, commensalism and parasitism is discussed. Next the symbiotic system of systems approach with respect to robotics is presented where concepts such as a paradigm shift from ‘Adapt and Survive’ to ‘Adapt and Thrive’ are outlined. Finally symbiosis applied to multi-robot fleets is presented highlighting the required cyber physical architecture and opportunities that exist when the HITL is linked to the diverse multi-robot fleet deployed in the field. In addition, the concepts for symbiosis across robotic platforms are also presented.

Chapter 6 provides an introduction to the robotic platforms and sensors integral to the symbiotic multi robot fleet within this thesis. The discussion entails a detailed exploration of the ground up capabilities and equipment of each robotic platform, elucidating their design applications. This encompasses a diverse array of robots, including wheeled, legged, and aerial robots sourced from various vendors including Clearpath, Boston Dynamics, DJI, Franka robotics and other bespoke equipment.

Chapter 7 includes the evaluation of the practical investigations integral to the thesis, presenting the diverse examples of symbiosis and HITL approaches. The chapter initiates with the presentation of a symbiotic system of systems design for an autonomous robot tasked with inspecting corrosion in an offshore wind farm substation. Utilising a Clearpath robot equipped with the non-destructive radar sensor, this section demonstrates a symbiotic relationship between the robot, different systems required to complete the objectives and HITL operator via a symbiotic digital architecture. The exploration continues with the introduction of a cyber-physical architecture designed for symbiotic multi-robot fleet autonomy. This marks the inaugural iteration of a symbiotic multi-robot fleet controlled by a HITL operator, specifically tailored within an analogue environment to represent an offshore wind substation use case scenario. The introduction of symbiosis across robots is introduced alongside the opportnities which exist when robots are able to symbiotically request assistance to overcome challenges in resilience, safety and reliability. The chapter culminates in the unveiling of a symbiotic autonomous robot ecosystem designed for post-operational cleanout in the nuclear sector. This ecosystem deploys a diverse range of robots dedicated to asset integrity inspection and radioactivity monitoring, showcasing the versatility and applicability of symbiotic autonomous systems in complex operational environments, which was presented to Sellafield Ltd.

In Chapter 8, the essential theories of radar and dielectrics are presented, coupled with a thorough examination of the microwave sensor accuracy across various use cases in this investigation for non-destructive evaluation within wind turbine blades, inspection of civil infrastructure and inspection for overhead line sag. Additionally, the chapter explores the application of radar for foresight monitoring within mobile robotic platforms. The primary objectives encompass assessing the proficiency of the sensor in detecting both surface and subsurface defects during asset integrity inspections, as well as enhancing situational awareness for robotic platforms, thereby contributing to heightened safety protocols.

In Chapter 9, the crucial discussion points threaded across this thesis are consolidated for ease of comprehension. Emphasised within are the opportunities and gaps for robotics in offshore and nuclear sectors, a concise summary of short-term and long-term objectives for robotics which are beyond the scope of near term work post thesis publication, and the identification of upcoming opportunities in metaverse applications.

Chapter 10 presents the conclusions drawn from this project highlighting conclusions from the key investigations and presents the value contributed from this work as a result of the investigations undertaken.

In Chapter 11, the future work of this thesis is presented where current near term objectives are presented and future pathways are proposed to reach the objective of symbiotic multi robot fleets for scalable resilient cyber physical systems.

Chapter 12 provides speculation, offering a series of forward-thinking predictions for the future landscape of the robotics field with respect to robots for energy infrastructure and scalable autonomy. The section aims to provide a visionary glimpse into potential trajectories and advancements within the realm of robotics. This speculative exploration aims to stimulate thought and imagination regarding the evolving nature of robotics, encouraging contemplation on possible future scenarios and innovations in the field.

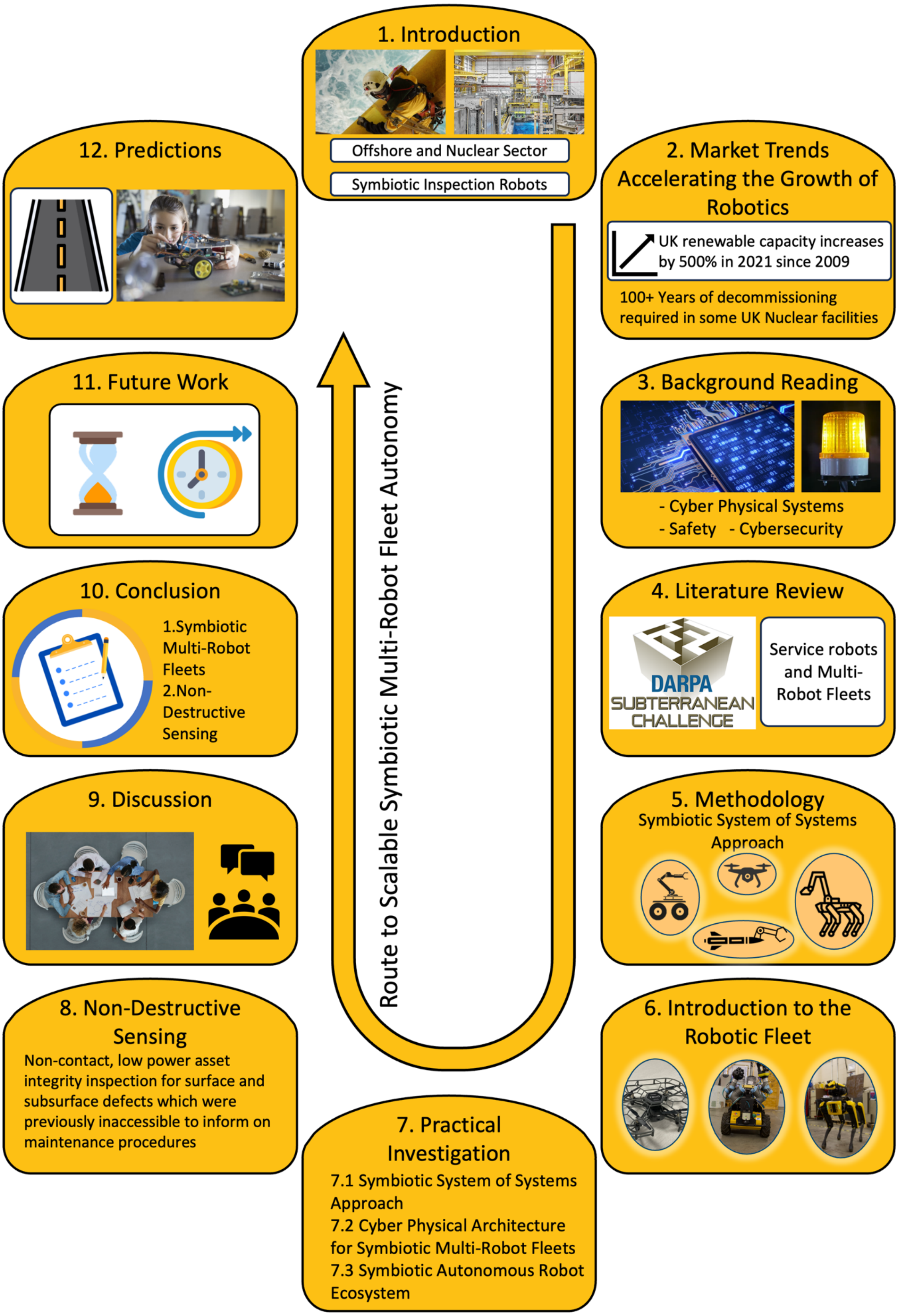


Figure 1-3 Thesis Structure Summary and key takeaway points.

2. Market Trends Accelerating the Growth of Robotics

Several trends exist globally and are contributing to the levelling-up of autonomy sector wide as this growth leads to a realisation of improvements due to robotics and artificial intelligence. These can be attributed to climate change, Covid-19 recovery, costs and improved technologies within the state-of-the-art. The investigated problems exist around key themes which include:

1. Safety to reduce the risks which humans take when conducting tasks around a energy facility
2. Resilience and Reliability where we can increase the frequency of IMR operations and ensure that these tasks can be undertaken under potentially hazardous operating conditions by robots
3. Increased operational overview via a cyber physical system as facilities get larger and more complex, this information should be available in an easy to access way for a human operator to verify the state and safety of the facility.

The United Nations Conference of the Parties 26 (COP 26) aimed to secure global net zero by mid-century and keep 1.5 degrees within reach. The Intergovernmental Panel of Climate Change identified that energy sector activities were clearly associated as the main cause of global climate change therefore, to reach these achievements, countries are aiming to phase out fossil fuels to accelerate deployment of electric vehicles, encourage investment into renewable energies and curtail deforestation [24,25]. It was identified that the burning of fossil fuels producing Carbon Dioxide (CO_2), represents two thirds of global greenhouse gas emissions [26]. Therefore, to meet the global targets set by COP 26, to mitigate these consequences, there has been significant investment in renewables [27]. The maturity of offshore wind technologies, combined with global political support for its expansion as part of international governments Covid-19 recovery stimulus, has resulted in this market experiencing unprecedent global growth [28]. Nevertheless, as the need for inspection, maintenance, and repair is common across various industrial sectors, there is a shared demand for similar robotic capabilities and skills. This chapter will delve into these trends, particularly focusing on two pivotal sectors: offshore and nuclear.

2.1. Offshore Renewable Energy Sector

With respect to the energy sector worldwide, the energy transition in response to climate change is resulting in significant investments towards net zero energy generation infrastructure [29]. Offshore wind represents a sector that is addressing challenges in Operation and Maintenance (O&M) via the deployment of robotic technologies, especially as wind farms upscale. In the United Kingdom, net zero infrastructure will represent an investment of £48B by 2050 [30,31]. This builds on considerable prior growth, with the UK renewable energy generation capacity increasing by 500% from 8GW in 2009 to 48GW in June 2021 [30–32]. In the United States, an offshore wind farm providing electricity to Block Island was taken offline, reverting to diesel-based power generation where a reported $30 million for the first segment of maintenance took place over several weeks. The issue related to the reburying of electrical cables [33]. For offshore assets, unaddressed or unforeseen problems can accelerate loss of revenue, leading to expensive stoppages and extensive repairs, as evidenced at Block Island as an example, therefore, inspection maintenance and repair techniques are essential to prevent this and must be applied on a 24/7 basis [33–37]†§. In the management of the complex, remote and highly distributed infrastructure, there are challenges such as: workforce resilience, cost reduction, lifecycle decarbonisation, and safety for human operators in dynamic operating environments [20,30,38,39]†. In 2018, it was reported that 80% of the costs associated in offshore wind farm O&M relates to the deployment of people onto offshore assets [40]. Furthermore, carbon intensive processes (e.g., field support vessels, helicopters.) are used when performing time or condition-based maintenance, representing a barrier in the sustainability of renewable energy infrastructure. This leads to a significant opportunity for a diverse robotic fleet to assist humans during the operation and maintenance of offshore assets, in addition to opportunities to reduce the amount of carbon in getting humans offshore in the first place for inspection.

2.1.1. Upscaling in the UK

The UK has created objectives and plans to increase offshore wind capacity from 22GW to 154GW by 2030. With such planned large growth, the plans are being created to deploy robotics and artificial intelligence to tackle lifecycle barriers to support profitable wind energy production and sustainability issues. The UK has positioned itself as a global leader in accelerating strategic investment into offshore wind projects [41]. Subject to significant investment and construction, the UK renewable energy capacity reached 47.4GW at the end of 2019, a 3GW, or 6.9% increase when compared to 2018. In addition, Offshore Wind Farms

(OWF) generated 31.9TWh of electricity representing a 19.6% increase when compared to the previous year. The total energy output of the UK in 2019 for both onshore and offshore wind energy production accounted for 9.9%, however in the first quarter of 2021, this increased to 25.6%, demonstrating a shift in energy provenance with a clear trend in favour of wind power [42–44]. In 2020, the UK produced approximately 6.8GW via operational offshore wind farms. With a future energy generation growth trajectory viewpoint including pre-planned, consented and projects under construction, this is expected to reach 27.2GW; increasing by 74.7% of installed turbine capacity. This increase can be attributed to the fourth round of Crown Estate offshore wind leasing where around 7GW of new seabed rights off the coast of England and Wales could provide electricity to 6 million houses [45]. Scotland also planned to offset 6 million tonnes of CO_2 via their first round of offshore leasing allowing investments of around £8 billion in the Scottish offshore wind sector [41]. An overview of the key trends presented can be viewed within Figure 2-1 [46–48].

The 2050 European Commission agenda estimated that around 250-450GW of offshore wind energy would be required to restrict global warming to within 1.5 degrees and estimates that up to 30% of future global electricity demand could be supplied via offshore wind energy [49,50]. To meet these estimations, an additional 40,910 11MW turbines would be required to cover an area of 75,250 km^2 (approx. the area of Ireland) with an estimated capital expenditure of $16.1billion and 2.5 million km for subsea cables alone by 2030 [51,52].

Effective policies and licences, technological advancements and cost reduction in O&M will ensure the continued growth of offshore wind. The UK has ensured a strong economic position by reinforcing the relationships between revenue support and an active UK supply chain. UK offshore wind projects currently being installed and operated have an estimated 32% UK content, generating around £1.8 billion per year, and with an expectation to rise to 65% by 2030 generating £9.2 billion per year [53].

The Covid-19 pandemic had a significant impact globally for both people and markets. In 2020, greenhouse gas emissions fell by 5.2% due to lower energy demands induced by social and economic disruptions however, this increased the next year by 6% reaching their highest

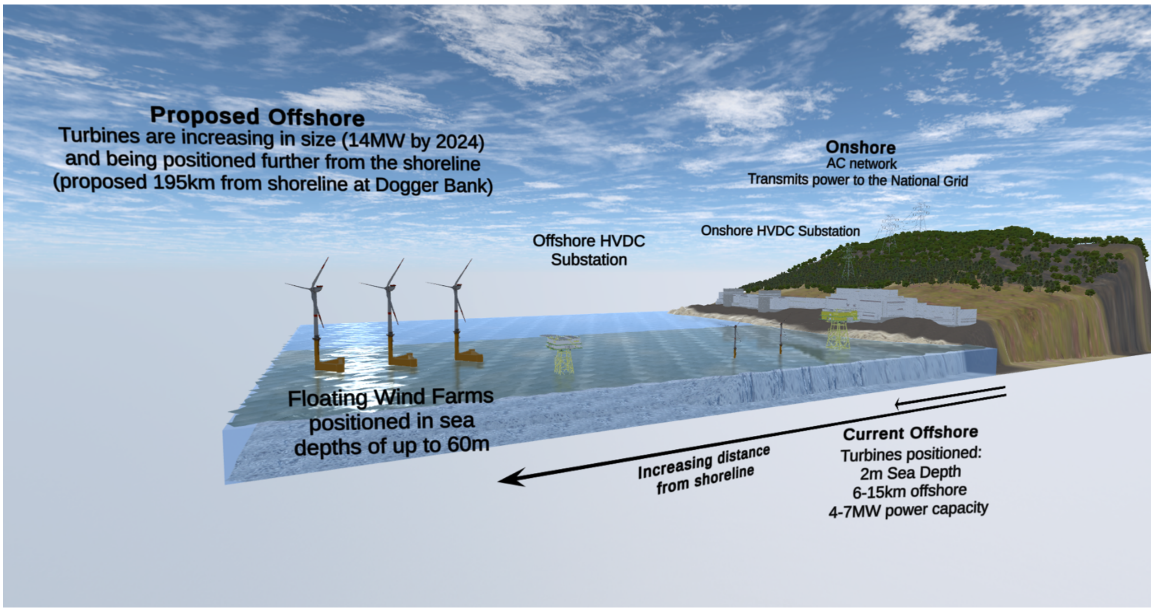


Figure 2-1 An overview of key targets in offshore wind farms [46–48].

level ever [54]. In November 2020, the UK Government released a ten-point plan to accelerate a ‘Green Industrial Revolution’ [30]. The aim was to increase green sector resilience in a post-pandemic economy, with support for green jobs and a route to accelerate the UK’s transition to meet net zero. Previous government support reduced the economic cost of offshore wind by two thirds in the previous five years where the ten-point plan aims to double offshore renewable infrastructure alongside increasing floating capacity twelvefold to 1GW with a commitment to produce 40GW of offshore wind power by 2030. Reaching these targets would require private investment of £20 billion in the UK and double employment within the sector [55]. An additional investment of £160 million will be made into modern ports and manufacturing infrastructure to strengthen the UK as a leader of manufacturing larger wind turbine blades. This would increase projects to 60% UK content through more stringent requirements for supply chains within contracts for difference auctions. The result of these initiatives is an increase in competitiveness globally and expertise whilst attracting investment for UK manufacturing [30,56–58].

A summary of the primary construction phases outlined by the Crown Estate can be found in Table 2-1 [59].

Figure 2-2 displays the current phases and timeframes of several proposed and under construction offshore wind farms. The creation of this data included merging data collected in 2016 and 2020 to give an increased understanding of the timelines provided by Renewables UK [60,61]. Unfortunately, information regarding the contracts for difference

Table 2-1 Primary construction phases outlined by Crown Estate [20].

Phase Number	**Phase Name**	**Description**
1	Development	Developer awarded the site by the Crown Estate.
2	Planning	The developer submit the planning consent for evaluation.
3	Contracts for Difference	Eligibility and secured - Projects which have secured a grid connection date with the National Grid and have received planning consent from the Crown Estate.
4	Pre-Construction	Planning permission consented however, the project has not entered the construction phase yet.
5	Under Construction	Construction offshore initiated.
6	Operational	The offshore wind farm has been commissioned and is generating power.

and operational phases was unavailable at the time of writing. Figure 2-3 presents the four remaining phases via merged data from Figure 2-2, with the duration assigned for each phase of the wind farm project. For the ‘In Development’ phase from 2016-2020, the average value presents a 277% increase in the efficiency of this phase. This represents the current challenge to industry as they have focused on this phase to ensure that offshore wind farms are designed and constructed rapidly. However, there are minor improvements in the other lifecycle phases. This could be caused by offshore wind farms being positioned further from the shoreline, with taller turbines and in more complex areas. Therefore, more approaches should be considered to tackle the issues in increased transportation durations, difficulties during installation due to deeper and more hazardous weather conditions further offshore. This data presents opportunities in improving and reducing the duration of the in planning, pre-construction and under construction phases. The highest impact measures to be taken when meeting net-zero targets would include using ecologically sensitive and less carbon intensive field support vessels and technologies. A second point includes the ‘In Planning’ and ‘In Development’ phases taking up ~40% of wind farm deployment duration. This represents an opportunity for improvement within this lifecycle phase of an offshore wind farm.

To secure a reliable, affordable and resilient supply from OWFs, offshore infrastructure requires a continuous and complex engineering cycle, associated with inspection, repair, logistics, maintenance and removal of subsystems [62,63]. There have been a number of advancements in technology which have reduced O&M costs. However, wind farm operators

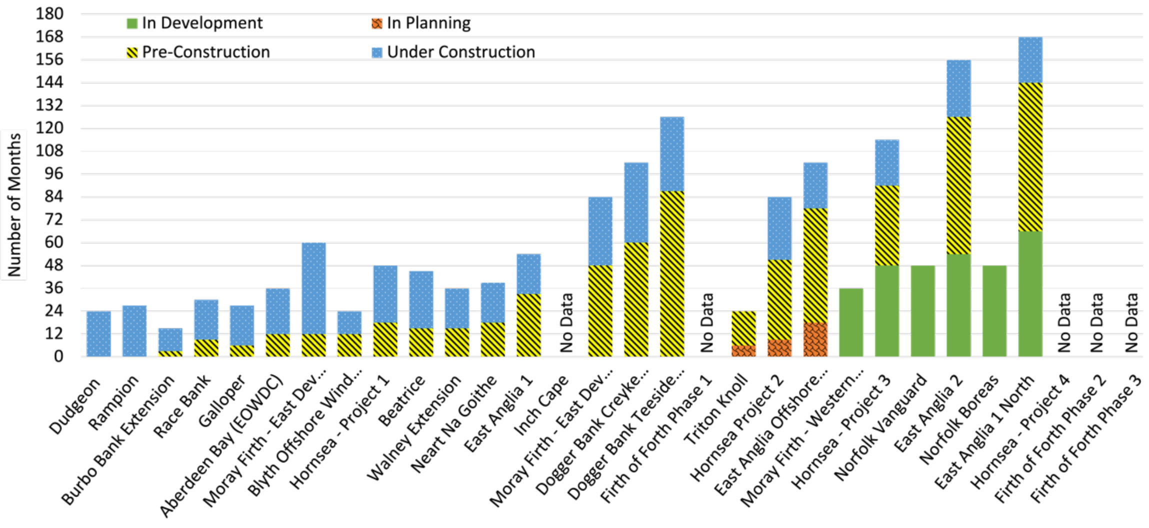


Figure 2-2 Timelines and current phases of offshore wind farm projects (2020) [60,61].

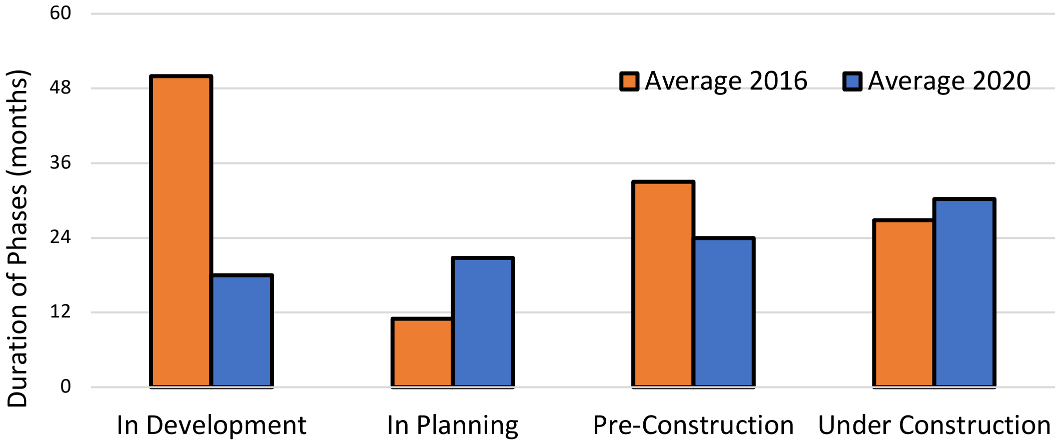


Figure 2-3 The average duration of key phases in the lifecycle of an offshore wind farm [60,61].

face several challenges which prevent them from achieving their roadmap to an efficient and sustainable OWF. While developments in Robotics and Artificial Intelligence (RAI) have the potential to positively shape the future offshore wind sector the challenges listed in order of importance include:

- Reduction of O&M costs – Expenditure of O&M accounts for up to 25% of the total lifecycle cost of an OWF. This barrier requires addressing to increase development in the offshore wind sector [64]. Turbine downtime, managing vessels and personnel, hazardous weather conditions, sea state and increasing distances to shore are all financial risks which inhibit the development of O&M. To create a reduction of costs, new operating procedures must be developed and implemented as standard and include RAI deployment for inspection, maintenance and repair. This allows for high frequency of intervention and inspection yielding improvements in quality of inspection and resulting in improved safety for personnel [65].

- Removal of personnel from dangerous environments – There is a need to improve safety within dangerous environments by reducing the presence of humans in these environments. This would minimise the exposure of the human worforce to hazardous weather conditions and sea states alongside accessing confined space areas representing a non-intervention challenge for robotic platforms [66].
- Lifecycle – Current methods of disposal of wind turbine blades include burial in landfills after approximately 25 years of service. Therefore, a key challenge to the ORE sector includes upscaling the recycling process for these materials [67,68].
- Recruitment - Recruitment shortages, currently existing in the sector at all skill levels due to competition from other offshore employment sectors and mainland jobs [69,70]. Additionally, there are challenges in training to ensure capturing knowledge effectively to upskill engineers and how technology can be used to create safe virtual training environments. This would allow skills to be tested in a ‘fail safe’ environment via virtual reality where humans can test their knowledge and make mistakes in a safe environment.
- Ecological issues in expanding offshore wind – Disruption and a potential long lasting detrimental effect on habitats and species which inhabit areas which currently require helicopters, crew transfer vessels, heavy jack up vessels and service operation vessels. These are used for maintenance of OWFs and as a hub for engineers to live on whilst offshore however are also carbon intensive [71].
- Emergent challenges include the reliability of supply chains from shore, as wind farms are situated further offshore and improvements to efficiency, while decreasing threats, via the application of big data analysis approaches and the detection of inaccurate datasets from offshore systems [72–74].

2.1.2. The Primary Support Functions and Lifecycle

Key lifecycle stages which have been assorted by the Crown Estate, industry and academia can be viewed in Table 2-1. However, an adjustment in approach is required to reflect the full lifecycle of an offshore wind farm array which considers optimisations across commissioning to decommissioning; the full lifecycle. This subsection highlights areas as displayed within Figure 2-4 where each coloured line represents information sharing to improve other elements of the lifecycle. For example, training can inform on procedures for all components of an offshore wind farm where all the phases include knowledge sharing and feedback on updates. Within Figure 2-4, the legend displays a ticked box highlighting areas which government, industry and academia have focussed on to date, whereas the hourglass symbol represents areas which require improvement in future.

2.1.2.1. Training

Operating in harsh environments requires safety to be paramount. There are also challenges which are faced when training as it can be difficult to do safely if conducting tests in real-world scenarios due to aspects such as weather conditions, working at height or underwater. It is time critical when serious injuries occur in offshore related environments where response times can be the difference between life and death. First responders have to maintain composure when in these situations and perform lifesaving operations which are undertaken under severe pressure. Offshore training conducted included where around forty paramedics conducted intensive working at height and rescue training delivered using a 27m high wind turbine training tower at the ORE Catapult at the National Renewable Energy Centre in Blyth, UK. Self-recovery, casualty recovery and emergency procedures when using vertical ladders and fixed fall arrest systems were conducted as part of the training programme. Training at facilities such as these maximises high levels of professionalism via key learnings attained from previous accidents and offshore emergencies [75]. Training can be simulated in two simulated scenarios such as 1) a training environment which is repurposed as safe, yet acts as a close representative to the real world environment. Typically these environments would have cameras recording the training so that participants can watch themselves back and learn from any mistakes. 2) The real-world environment however under controlled variables such as good weather conditions and with a supervisor overseeing the procedure taken. However, whilst risks are reduced for these scenarios, it is important to be aware that risks are still involved when conducting exercies in these environments. Therefore, immersive reality could be very useful in future to further reduce risks ahead of conducting potential dangerous activities at height or under other pressures when operating exercises in the real world.

The AI Sector Deal introduces several measures to ensure the primary role of offshore wind energy in the future and includes key points related to workforce and training. Key statistics identified in the report are presented in Figure 2-5 and aims to increase the skilled workforce from 10,000 in 2017 to around 36,000 by 2032 [76]. This increase can be attributed to a threefold increase in the number of turbines from 1660 to 5,358 by 2032, and with an

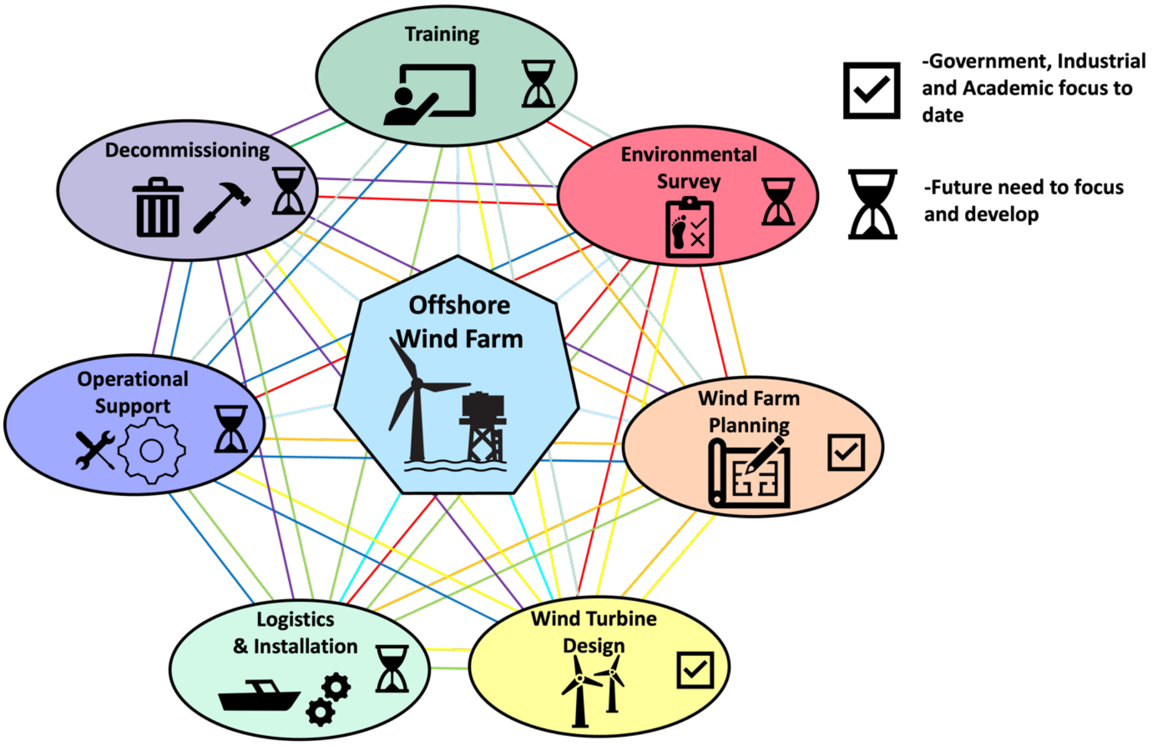


Figure 2-4 The key elements and functions of an offshore wind farm where each coloured line presents interactions to improve on procedures across each major element representing the full interconnectability of the lifecycle and extending remaining useful life [20]†.

expected fivefold increase in installed capacity from 6.4GW to 35GW over the same period [77]. The report also highlights the transferability of skills from other sectors, where the core entry pathways into the engineering sector will continue to be from technically related industries, such as the armed forces and those from the wider energy sector. Opportunities for apprentices and graduates will continue to exist and provide foundations of new experience for future generations wih the inclusion of people with skills applicable across sectors such as in IT, commercial, data analytics and ROV operators [77]. Even with a high number of students in engineering university courses currently, it is likely that the UK will be short of 20,000 engineering graduates per year to meet this demand for a green future [77,78]. It was also identified that 400,000 new energy workers will be required in the future workforce to ensure that the UK achieves net zero. This requirement provides opportunities for skilled tradesmen, engineers and other specialists across the UK/globe to assist in the installation of low-carbon heating and development of new methodologies [79].

To reach these targets this will require academic, industrial and government to promote STEM educational progression, clear pathways and opportunities. This can be achieved via a clear curriculum to increase job mobility between sectors and apprenticeship opportunities [57]. The facilitation of this must be created via clear partnerships between these types of

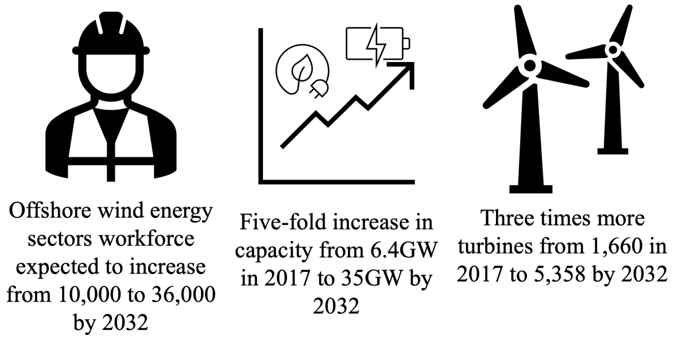


Figure 2-5 Key statistics within the offshore wind energy sector [77].

institutions to create effective engagement for students. To attract a wide variety of skilled people they must also develop innovative methods. To produce and reassure investment in skills and education across the supply chain for the current workforce, a procurement skills accord must be created. To assist in the transfer of skills between companies, technologies and other sectors, the implementation of common training standards must also be implemented. This would generate and encourage various pathways for individual development [77].

2.1.2.2. Environmental Survey

Meticulous planning goes into the proposal when planning for an offshore wind farm. Development and consenting services are undertaken until financial close or full commitment from the operators to begin construction. This can only be achieved once all environmental surveys, metocean assessment, and geological and hydrographical surveys to decrease the detrimental effects to any sea life that reside in the ocean during construction is completed [59].

Man-made construction and operations typically cause a detrimental effect on wildlife therefore measures must be in place to minimise these risks. To reduce as many negative effects as possible, assessments on the physical, biological and human environment during these phases will lead to an ecological strategy which is more sustainable during the planning phase. An evaluation of the impact of the wind farm at the intended location and surrounding areas is conducted during the environmental survey. Some of the studies undertaken include ornithological, benthic with sediment and seabed, fish and shellfish and marine mammal surveys. This establishes abundance, diversity, distribution and behaviour of wildlife. Albeit there are several negative effects during the construction phases, there are also notable benefits where for example shellfish utilise wind turbine foundations as artificial reefs. This encourages ecosystems for multiple species and habitats for animals which prey on them [80].

2.1.2.3. Wind Farm Planning

Wind farm planning is a vital phase which should be undertaken to ensure a seamless construction phase which follows. A well-ordered plan ensures successful installation of the offshore wind farm without meeting any problems which could extend the project timeline (which can be costly). Considerations must be made to subsea cabling, grid connection, number of turbines, foundations, substations, installation companies, operational port and operational base. The full scope of the project is defined in the planning phase where clear objectives are outlined, achieving minimal impact on the environment, high quality design, optimum standards of safety and a recovery strategy to boost nature to return after successful completion.

To ensure foundations are safely and properly fabricated, wind farm operators are required to understand the depths of the seabed to identify any areas that are not secure for foundations. A geophysical survey for boulders and unexplored ordnance was published by the Carbon Trust Offshore Wind Accelerator [81]. The guidance supports subsea cable installation by improving the efficiency and accuracy of surveys. For example, two wartime explosives weighing 500lb each were discovered in the area of Rampion wind farm during the construction phase in 2016. They were retrieved and disposed of by E.On [82]. Previous discoveries of unexploded ordinance include the previous year when seven devices were found on the seabed at a planned offshore wind farm in the wash of the Lincolnshire coast [83]. For future offshore wind farms it will be important that planning phases cover unexplored, deeper waters. This presents a requirement to precisely use data from geophysical investigations in the planning stages to form information for risk assessment and organisation of these procedures which are highly impactful reducing costly and life-threatening accidents [84].

2.1.2.4. Wind Turbine Design

The evolution of wind turbine design has primarily been driven by the global requirement to develop reliable and clean energy sources. Designers are utilising engineering expertise and algorithms to improve turbine design and wind farm array design. Wind turbine design typically addresses how an engineer can ensure the efficiency of a wind turbine by assessing variables such as aerodynamic efficiency, turbine blade length, drivetrain and nacelle type. This typically uses analysis software to assess variables such as number of turbines in an array, size of turbines used and weather conditions experienced in the area [85].

To date, high-pace competition between large multinational manufacturers has helped to refine mechanical and electrical designs rapidly to ensure the successful, reliable and long-term useful life of wind turbine assets. Offshore wind costs have declined from £150 to £40 per Megawatt hour (MWh) and, as a result, turbine designs have improved to capture higher wind speeds and be positioned further from shore. The high initial costs during the inception of offshore wind turbines stem from the expenses incurred in their manufacturing and design phases, which subsequently decrease as manufacturing approaches evolve. As affordability increases among customers, there's a shift towards greater cost-effectiveness, leading to wider adoption of wind turbines [86].

Limiting factors which have inhibited development further offshore include cost of logistics, safe remote operations and harsh weather conditions located in deeper waters. However, with these risks and challenges comes reward as wind turbine designers follow key drivers for continued development due to more efficient energy generation (higher winds further offshore) and more affordable electricity for consumers [87–89]. An area which has not yet faced evolution is the specifications for regulating the quality of power to the grid. These can be summarised and address aspects such as flicker, voltage change, control systems to ensure reliable connection and steady state operation [59,90].

Key competitors include GE Renewable Energy, Siemens Gamesa and MHI Vestas who have led the race in creating efficiency and reliability improvements in offshore wind farms to date. As highlighted in Table 2-2, this has resulted in technology development within increasing blade lengths to capture larger swept areas of wind to return larger generated power capacities. To meet the requirements to sustain the operation of these larger turbines offshore, there is a need to situate these turbines further offshore exposing these highly complex assets to deeper waters, higher windspeeds, harsher conditions resulting in the design of floating wind turbines [88,89].

Offshore and onshore wind turbines require different design restraints allowing for opportunities to manufacture these assets larger and more efficiently to create more powerful turbines [85,91–97]. This increase in turbine size has not met the improvements required to

Table 2-2 Increasing wind turbine designs correlated by date of design [20]†.

Company (Reference)	Offshore Turbine Name	Current Offshore Distance from Shoreline UK	Tower Height (m)	Blade Length (m)	Swept Area (m^2)	Power Capacity (MW)	Serial Production
Siemens Gamesa [91]	SWT-3.6-120 Offshore	6 km (Burbo Bank) [46]	90	58.5	11,300	3.6	2007
Siemens Gamesa [92]	SWT-7.0-154	13km (Beatrice) [475]	90	75	18,600	7	2017
GE Renewable Energy [93]	Haliade-X 12	195 km (Teesside A at Dogger Bank)	260	107	38,000	12	2019
MHI Vestas [94]	V174-9.5	N/A	110	85	23,779	9.5	2019
Siemens Gamesa [95]	SG 8.0-167 DD	89 km at Hornsea 2	Site Specific	81.4	21,900	8.0	2019
GE Renewable Energy [96]	Haliade-X 13	195km (Proposed 190 units at Dogger Bank [47])	248	107	38,000	13	2020
MHI Vestas [94]	V164-10.0 MW	6 km (Burbo Bank)	N/A	N/A	21,124	10	2021
Siemens Gamesa [85]	SG 11.0-200 DD	N/A	Site specific	97	31,400	11	2022
Siemens Gamesa [97]	SG-222 DD	195 km (Teesside B at Dogger Bank)	Site Specific	108	39,000	14	2024

inspect turbines though. Inspection standards to date consist of personnel and remotely controlled robots overcoming weather conditions and height to complete inspections [98,99]. Initial challenges within inspection include overcoming difficult-to-reach access areas at height such as within the substation, nacelle tower and blades.

AI and neural networks have an opportunity to improve wind turbine and wind farm array design. This could allow operators to improve return on investment via optimised maintenance procedures. For example in a specified area, the optimum number of wind turbines could be calculated for different types of wind turbine sizes and designs. Within wind turbine design, neural networks could be utilised to optimise aerodynamic variables such as drag and lift coefficients, angle of attack, Reynolds number and viscosity. This would improve a full systems efficiency alongside informing design operation for wind turbines via power electronics, control strategies and materials [100,101].

2.1.2.5. Logistics and Installation

OWF operators require a modern logistical service system to overcome the hazardous offshore environment. Logistics of the required infrastructure includes the organisation and movement of equipment or personnel from land to an offshore site. The required supporting infrastructure and logistics solutions is displayed within Figure 2-6. As illustrated, the lifecycle of an offshore wind farm is heavily reliant on installation vessels (A), crew transfer vessels (B), subsea divers (C) and helicopters (D) [102]. Skilled technicians are crucial when operating equipment where they are often required to ensure the correct heavy lift vessel is selected and prepared properly to minimise risks in safety from catastrophic failure.

For the offshore workforce, a commute often includes overcoming rough sea states for up to four hours before work begins, therefore Service Operations Vessels (SOVs) are crucial, acting as a floating hub for technicians to live on and store components to ensure the operation of the OWF. SOVs are large and can allow up to 88 personnel to live onboard for around 4 weeks whilst completing work. For accessing each wind turbine, a gangway system counterbalances the effects of the waves to provide rapid and safe access to complete inspection, maintenance and repair [102]. Helicopters can also be used offshore however, are only typically used for rapid deployment or emergencies requiring healthcare treatment. All offshore materials are extremely expensive to deploy however, this maximises yield and are deployed strategically to minimise costs [103]. Lastly, these methods of deployment are carbon intensive and often present several risks to personnel due to the hazardous offshore environment. In future, it is necessary to reduce the carbon footprint of such vessels to more efficient vessels that are battery or hydrogen powered.

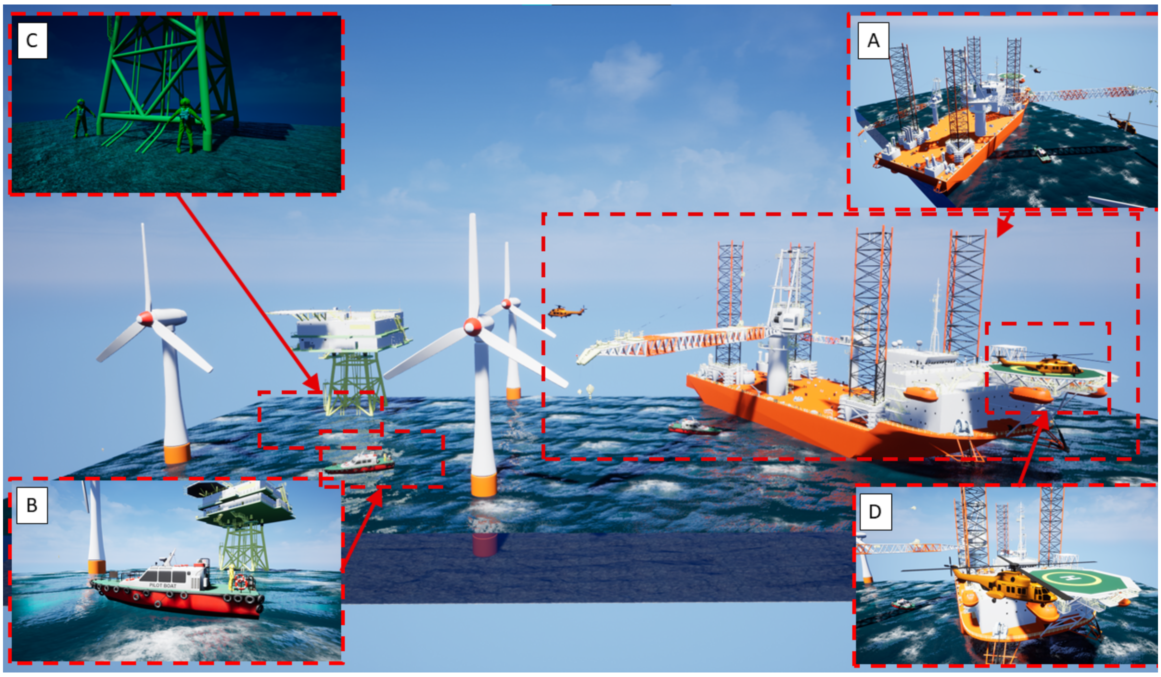


Figure 2-6 Current assets and the supporting infrastructure within the lifecycle of an OWF array [20]†.

An in-development phase includes robotics and AI to support the installation of an OWF array. Criteria to date include that the focus has been on robotics and AI to support the O&M phase of an OWF as these robotic systems are not quite at the standard yet to be fully trustworthy to install components and equipment, hence, work to date has mainly focused on the O&M phase to build levels of trust. Several challenges and opportunities are faced for robotics in the installation of an OWF. This includes the creation of a fully autonomous system that is large and powerful to accurately transfer heavy components into the correct positions and follow safety procedures throughout the installation phase [104]. Improvements do also exist for off-the-shelf solutions where autonomous operations would lead to safe operations within all weather extremes, lowered risk for personnel and decreased human intervention. Digital Twins (DTs) also present significant opportunities to reduce human intervention whilst increasing visibility as a digital version of an asset and environment can be viewed. Examples include updating preparation activities in the lead up to logistics of heavy components. For a multi-robot fleet, this includes the mooring and transportation of the foundations and other instances where robots could be deployed within a nacelle to provide updates on the positioning of a blade during the guiding for installation.

2.1.2.6. Operational Support

Improvements in the lifecycle functions (Figure 2-4) has led to a deepening knowledge within the offshore wind sector. Research within O&M procedures aim to improved decision making in the remaining useful life of an asset to reduce costs and risks [105,106]. Operational support includes many above sea activities but also includes inspection and maintenance of subsea cables, foundations, substation and cables on land connecting to the national grid. For example, the cost of locating and replacing a segment of damaged subsea cable can vary from £0.6-1.2 million and approximately a loss in revenue of £5.4 million per month from a power outage of a 300MW offshore wind farm [107–113]§.

The maintenance of subsea cables represents a significant challenge as they are difficult to inspect due to high currents, deep water and harsh weather conditions. However, new sensing methods can be deployed as payloads on surface and subsurface vessels to track subsea cable positions and determine their state of health. OWF operators are required to provide a reliable service in providing electricity to the national grid. Disruptions to this service can result in not only a loss of revenue for operators but also expensive fines from energy regulators. Online condition monitoring systems have focused on internal failure modes such as localised heating inferring overrated current use, partial discharge or degradation of dielectric insulation. Visual observation of external integrity and position of the cable (buried, unburied, strumming) on the seabed is used within external condition monitoring. Subsea robotic platforms can reduce risk to personnel as they can operate under different underwater conditions that the seabed is applied to. Subsea sensing mechanisms paired alongside predictive maintenance can be used to verify the performance and integrity of underwater cables [111,113,114]§.

Robotics is increasingly being considered as a primary tool for inspection, maintenance and repair of offshore assets within operational support and O&M. This is attributed to robots significantly advancing their capability including competency to complete tasks and manoeuvrability. This is in addition to reductions to risk of offshore personnel and improvement when relaying information to remote operators.

2.1.2.7. Decommissioning

The decommissioning aspect of an OWF is a growing and relatively new market as wind farms reach the end of their lifecycles. Whilst well-structured plans are in place to perform decommissioning tasks, engineers will continuously learn and improve these processes. Since 2016 decommissioning has only been performed on offshore wind turbines at depths of less than 50 metres. This represents an opportunity for teams to learn in less hazardous and difficult conditions near the shoreline [115]. There are also opportunities to repurpose and reuse key components therefore, complete dismantling and disposal should not necessarily be the priority in the decommissioning phase. This can include refurbishment activities of minor components such as rotor or drivetrain, and where viable, reuse of major components such as foundations, tower and cables. This enables for current projects to extend their remaining useful life of assets and increase/maintain energy production in certain areas too. The introduction of wind turbine decommissioning marks a significant achievement for the offshore wind industry, incorporating valuable insights from the lifecycle development of wind farm arrays. Despite the first decommissioning of farms taking place in 2016, the process is still in its developmental stage, with numerous procedures yet to be standardised [115].

Despite their contribution to clean energy production, the existing design of wind turbines results in significant waste generation, with each turbine producing several tons of waste at the end of its lifecycle. Although approximately 85% of the turbine components can be recycled effectively, the predominantly fiberglass composition of the blades poses challenges for environmentally friendly disposal [67]. From September 2019 to March 2020, a total of 1000 end-of-lifecycle fiberglass wind turbine blades were decommissioned and subsequently buried at a landfill facility located in Casper, Wyoming, USA (Figure 2-7). Typically, all the blade elements, including shear webs, load-carrying beams, leading and trailing edges, and the aerodynamic shell, are integrated into a single-piece component during the manufacturing process. This construction method makes it challenging to separate the components for disposal, and it usually necessitates the use of a diamond-tipped saw blade with ample water cooling [116]. As a result, the durability of these materials, which is highly beneficial for maintaining asset longevity during the energy production phase, also renders them challenging to recycle. To tackle this issue, small to medium enterprises such as Global Fiberglass Solutions are providing green-product manufacturing via specialising in fiberglass recycling services [117]. However, the availability of these companies is inadequate to meet the current and future demand resulting in a substantial backlog of wind turbine blades either in landill or awaiting recycling. This will necessitate significant upscaling of the methods employed by new or expansion of companies like Global Fiberglass Solutions to address the global demand for waste disposal. Global Fiberglass Solutions, headquartered in Bellevue, Washington, USA, specialises in transforming fiberglass composites into small pellets suitable for conversion into injectable plastics or waterproof sheets, which can then be reused in new construction projects [68,117]. The ongoing expansion of wind farms and their installation will lead to a rise in decommissioning, offset by the typical life expectancy of a wind farm (currently 20-25 years). Pyrolysis offers

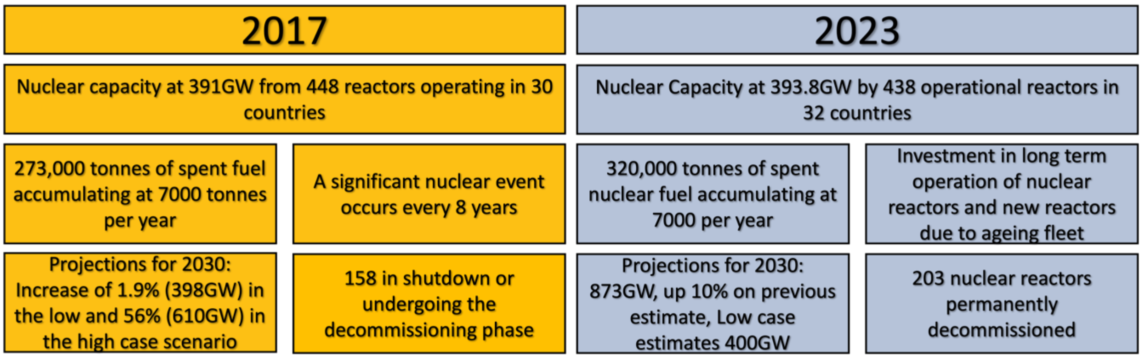
Figure 2-7 Decommissioned wind turbine blades awaiting burial and disposal at Casper Wyoming [68].

an alternative method for recycling wind turbine blades, involving the slicing of the blades and placing them in ovens operating at temperatures ranging from 450 to 700°C. The outcome of this process yields materials that can be utilised in various applications such as glue, paint, and concrete. Additionally, the pyrolytic process produces valuable by-products like syngas, which serves as a fuel source for combustion engines, and charcoal, an excellent fertiliser [68].

2.2. Nuclear Sector

With respect to achieving net-zero targets globally, Nuclear power generation is an important low-emission source for producing electricity where in 2021, around 10% of global electricity generation was contributed by the nuclear sector. Historically, nuclear energy has been one of the largest global contributors of carbon-free energy, having real potential to contribute to decarbonisation of the power sector [118]. However, it is well known the challenges and catastrophic consequences if radioactive waste is not stored safely. Namely, Fukushima and Chernobyl [119–121].

Figure 2-8 presents key statistics from the International Atomic Energy Agency with a comparison between 2017 and 2023. In 2017 it was presented that on average, a significant nuclear incident occurs approximately every 8 years where at the time of this report there had been approximately 100 nuclear accidents reported (minor and major incidents). In comparison between 2017 and 2023 there was a difference of 10 new reactors operating where two new countries were operating nuclear reactors. However, it shall be noted that in the approximate 5-year difference in time between statistics available, only 2.8GW of new nuclear capacity has been installed. This can be mainly attributed to many nuclear facilities reaching the end of their 30-40 year lifecycles hereby reaching the decommissioning phase (158 shutdown by 2017 and a further 45 shutdown by 2023). In terms of spent nuclear fuel an accurate prediction of approximately 7000 tonnes per year is consistent between 2017 and 2023 where the figures match this comparison since approximately 7833 tonnes per year has been produced resulting in 320,000 tonnes during this period overall [122]. The projections from 2017 are on track to make the low end of 398GW however, have since been changed to meet the future demand where it is predicted that nuclear capacity is set to double by 2030 according to figures [122–125].



2017		2023	
Nuclear capacity at 391GW from 448 reactors operating in 30 countries		Nuclear Capacity at 393.8GW by 438 operational reactors in 32 countries	
273,000 tonnes of spent fuel accumulating at 7000 tonnes per year	A significant nuclear event occurs every 8 years	320,000 tonnes of spent nuclear fuel accumulating at 7000 per year	Investment in long term operation of nuclear reactors and new reactors due to ageing fleet
Projections for 2030: Increase of 1.9% (398GW) in the low and 56% (610GW) in the high case scenario	158 in shutdown or undergoing the decommissioning phase	Projections for 2030: 873GW, up 10% on previous estimate, Low case estimates 400GW	203 nuclear reactors permanently decommissioned

Figure 2-8 Statistics from the Nuclear Technology Review 2017 versus 2023 [122,125].

Since the devastating effects of the Chernobyl accident in 1986, many countries have begun to iteratively decommission their nuclear facilities and only typically use nuclear facilities for peaceful purposes. This is due to considerations in the risk of future nuclear meltdowns, impacts on human health and environment and the unresolved issue for disposing of nuclear waste. In February 2022 at Chernobyl, it was reported that the radiation levels were up to twenty times above the normal following heavy fighting between Russian and Ukrainian militants in the region [126]. However, despite these risks, plans and intentions to decommission nuclear facilities, it is expected that worldwide nuclear electricity generation capacity will keep increasing until 2050 where most facilities decommissioned will be older nuclear facilities at the end of their lifecycle [127].

The UK currently has plans in place to decommission its current nuclear capacity by almost half by 2025 with only a single new plant being constructed at Hinkley Point C. With the current trajectory, if no other new nuclear power stations are constructed (as of November 2023), then the UK nuclear capacity could be a third of what it was in 2021 by 2050 [128]. However, there is still a significant commitment to appropriately manage decommissioned sites where the UK is predicted to spend in excess of £130 billion over the next 120 years [127]. Whilst the UK predominantly plans to decommission, the global figures display an increasing trend of nuclear capacity by about 0.3% increase year-on-year where in 2022 nuclear power capacity increased by around 1.5GW. Around 60% of new capacity additions were contributed by emerging market and developing economies, with over half of decommissioning occurring in advanced economies such as Belgium, the United Kingdom, and the United States [118].

Nuclear reactors are very useful in providing energy security at times where renewable energy is unable to meet demand where Figure 2-9 presents a challenging, cluttered

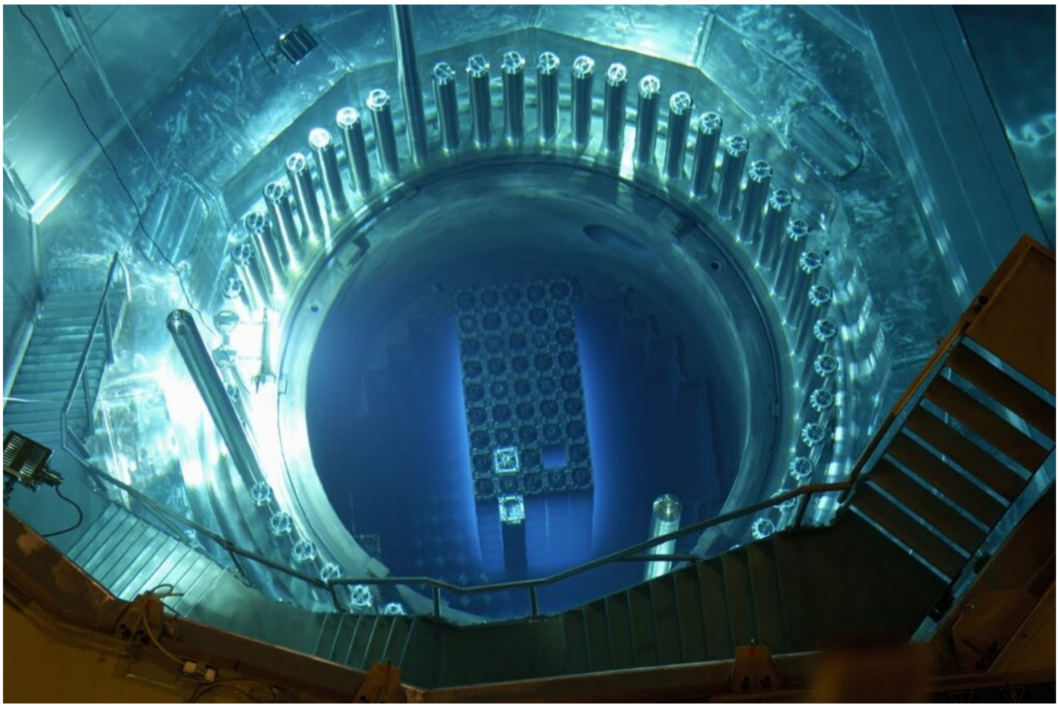


Figure 2-9 Cherenkov radiation effect (blue light) displayed on a nuclear core [130].

environment with confined spaces for subsea vessels to navigate if required to conduct inspection activities [129,130]. Nuclear power plants play a role in ensuring electricity security through various means, including maintaining stability in power grids and supporting decarbonisation strategies. To a certain extent, they can adjust their output to align with fluctuations in demand and supply. As the proportion of variable renewables, such as wind and solar photovoltaics, continues to grow, there will be an increasing demand for these services [118].

Supporting infrastructure is being established including the creation of small modular reactors with potential to expand opportunities for nuclear power in addition to complementing the production from hydrogen technologies and district heating networks. Small modular reactors, specifically, are available in various sizes, configurations, and output temperatures, allowing them to be applied in other industries where large light water nuclear reactors, due to their physical size and lower temperature requirements, are not suitable. Exploring these markets has the potential to allow nuclear power to fully realise its capability within the global energy transition [131].

2.2.1. Support Functions of Robots in Nuclear

Nuclear chain reactions for generating electricity have led mankind to the extensive discovery and development to get the nuclear sector to its position to date. Nuclear energy has a high energy density which requires a small amount of fuel, hence, to date it has been exploited extensively. The design and construction of nuclear facilities have led to the establishment of environments where access has been limited. This limitation is primarily attributed to the risks associated with high levels of radiation exposure. Additionally, space constraints and the presence of toxic and combustible atmospheres contribute to the restricted access for humans in these environments. Safety holds paramount significance. Initially, in 1979, long-handled tools emerged as innovative instruments to enhance safety for nuclear operators. However, since then, engineering advancements have facilitated the development of highly sophisticated systems and designs, significantly contributing to safety in inspection, maintenance, and repair tasks alongside methods to monitor radiological activity [124,132].

2.2.1.1. Maintenance

Attentively overseeing nuclear facilities is critical, driven by safety considerations and the prolonged half-life of nuclear waste products. Several components within these facilities are constructed using reinforced concrete elements. Possible degradation mechanisms of reinforced concrete encompass a range of factors, including corrosion of reinforcement, alkali-silica reaction, freeze-thaw cycling, sulphate attack, deformation mechanisms like creep and shrinkage, stresses induced by structural constraints combined with seasonal effects such as thermal cycling and precipitation, and exposure to extreme events [133]. Strict quality control should be implemented across similar stages as presented in the ORE sector as in subsection 2.1.2 The Primary Support Functions and Lifecycle. These mainly consist of planning, construction, operation and maintenance activities throughout the operation and decommissioning phases [134]. The deterioration of reinforced concrete in spent fuel pools and related nuclear facilities is a prevalent concern, necessitating IMR activities to ensure the safe operation of the plant. Engineers commonly address degradation mechanisms such as corrosion in steel-reinforced concrete and thermal cracking through necessary repair measures.

2.2.1.2. Normal Monitoring of Radiological activity

To ensure the safety of an operational or decommissioned site, regular inspections are made to monitor the radiological activity throughout a nuclear facility. Key objectives of monitoring are to provide information to [135]:

- Check that systems for effluent treatment and control are performing properly.

- Identify any early warning signs from normal authorised operation.
- Detect any unpredicted changes in activity concentrations and to evaluate long term trends in environmental radiation levels as a result of discharge practise.
- Provide information to the public.

Gaining this type of information is conducted in a continuous method of testing via automated measuring networks and intermittent way via periodic sampling around a facility [135].

Three types of ionising radiation exist and are required to be monitored. These include alpha (α), beta (β), and gamma (γ) respectively. A sheet of paper is sufficient to block alpha particles, and these particles pose a threat to humans only if they are ingested. They are generated by uranium or transuranic elements which are typically heavy meaning they are only detectable in near proximity (~2cm from source). Beta radiation is generated by a range of radioactive elements and is more penetrative than alpha radiation, however, is less harmful and straightforward in the shielding (where effective shielding can be achieved from 1cm of plastic). A higher energy electromagnetic wave that is highly penetrable and difficult to shield from includes gamma radiation. Nuclear workers are required to wear personal dosimeters to measure their levels of exposure. Gamma radiation requires barriers of lead, concrete or water to provide sufficient protection and can cause damage through human tissue and deoxyribonucleic acid (more commonly known as DNA) often causing cancer [136].

2.2.1.3. Storing of Waste

Nuclear waste can be divided into three categories: low level waste, intermediate level waste and high-level waste. Low-level waste is typically incinerated or processed as ordinary waste and typically includes materials which produce small amount of radioactivity such as paper, tools or clothing. Intermediate level waste typically requires shielding due to it having higher radioactivity and typically includes chemicals, resins and metal fuel cladding. High level waste includes spent nuclear fuel and products from the fission reaction which generates the highest amount of radioactivity. With radioactive half-lives in the order of millions of years, spent nuclear fuels require significant care in handling. Typically, deep geological disposal is preferred where waste is buried at depths of 300-800m below the earth surface. However, currently there are no fully-functional waste disposal repositories. In addition, a key segment in reaching this phase includes storing nuclear waste in cooling ponds as they still

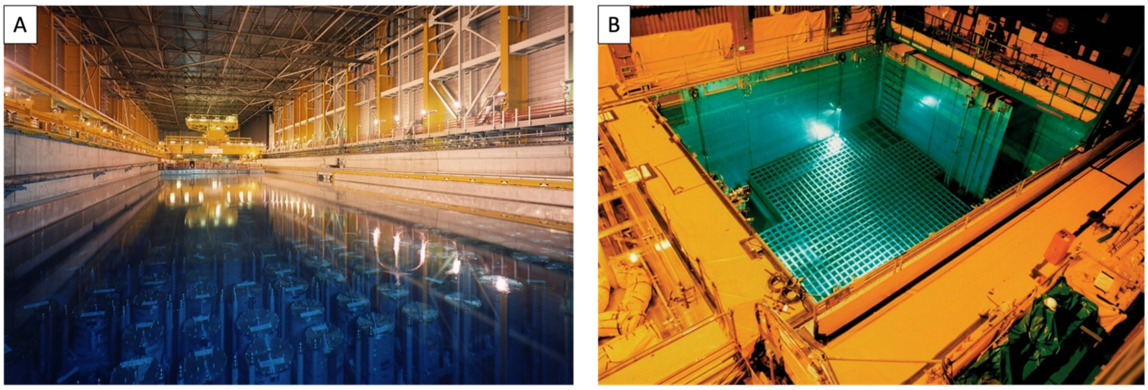


Figure 2-10 Images of Spent Fuel Ponds at (A) Sellafield Ltd, UK and (B) San Onofre California, USA.

continuously generate heat for 20 to 60 years. This requires the cooling pond to be continuously monitored for temperature hot spots and leaks in the storage canisters [137].

Radiological activity presents a significant challenge in underwater environments. At Sellafield Ltd in the UK, there are 240 on-site buildings designated for the storage of radioactive materials. Among these facilities, four buildings are categorised as 'high hazard' areas, encompassing legacy ponds and silos constructed in the 1940s for the containment of nuclear waste. These storage ponds are the size of Olympic swimming pools and around 10m deep containing waste dating back to the 1950s [138]. The storage pools are typically well lit with smaller segmented walled areas as pictured in Figure 2-10. Current approaches to inspecting and monitoring spent fuel ponds involve deploying a mobile bridge, with personnel performing inspections using sensors. These tasks are frequently repetitive and time-consuming [139]. A challenge arises in conducting inventory assessments of certain ponds, as some bays have been sealed for several decades, allowing access only through a 150mm diameter hole. Consequently, challenges persist in the development of underwater exploration vehicles capable of characterising and monitoring storage facilities [138].

2.2.1.4. Emergency Radiation Monitoring

Whilst safety is the priority of all nuclear sites, there is a risk that an accident may happen despite many complex and rigourous safety measures in place. Normal radiation monitoring was discussed previously in section 2.2.1.2. Emergency monitoring is a key procedure which should be in place to rapidly and adequately assess the need for protective actions making use of all available information [135]. Several methods should be put in place when an emergency situation occurs and are displayed within Table 2-3.

Table 2-3 Emergency Radiation Monitoring Techniques [135].

Method	**Description**
External Dose Rate	- Stationary automated systems or portable systems for dose rate monitoring - Integrated dose
Airborne Radionuclide Concentrations	- Stationary filter stations equipped for online measurements, collection for lab measurments, advanced sampling (online iodine sampling) or collection of iodine measurment - Mobile air-sampling stations (gross beta measurements or gamma spectroscopy for lab analysis) - Aerial sampling at high altitudes (gamma spectroscopy in lab)
Deposition Measurements	- In situ measurement of surface activity on the ground (gamma spectroscopy) - Aerial measurements of surface activity - Environmental Samples
Foodstuff and Environmental Contamination	- Sampling and measurements in lab for α, β and γ
Individual Dose Measurements	- External exposure (dosimeter) - External containation (α, β and γ) - Internal contamination screenings - Internal contamination measurements (gamma spectroscopy) - Excretion measurements (lab analysis) - Individual accumulated dose (biological dosimetry)

The most recent Nuclear disaster occurred in 2011 at the Fukushima Power plant which resulted in an adhoc emergency response strategy. Improper planning led to confusion and inefficient emergency evacuation procedures. The emergency radiation monitoring was summarised under the categories of ground-based and aerial monitoring. Whilst airborne monitoring took place almost immediately after the accident, it took 11 days to process the results from the investigation. In addition, ground-based monitoring took 4 days to take place as it was deemed unsafe to proceed due to risk of exposure to excessive radiation [123]. It must be noted that in most cases helicopters were used to measure ambient dose rates via portable survey meters suspended at 1 meter height above the ground by a wire [140].

2.2.1.5. Radiation Hardening for Hardware Systems

Whilst it is impressive that robots are tasked with IMR activities for a large variety of sectors, the nuclear sector faces an additional challenge which significantly plays a detrimental role in the operation of a robotic platform. Radiation is a non-visible threat to a robot which damages the operation of active electronics which are vital in the operation of a robot. This can lead to permananent failure or temporary alterations in behaviour via single event effects or cumulative effects [141]. Radiation hardening tolerance is an active area of research with the aims to extend the durability of electronics in ionising environments so that hardware can withstand higher levels of radiation dosage and more significant ratios of accumulated radition [142–144].

Whilst robots naturally hold a higher tolerance to radiation than humans, there is still a zone where electronics fail due to radiation. In addition, when providing increased levels of autonomy , this requires more complex electronics and circuitry which is expected to be less robust to ionising radiation when compared to simpler control methods. Therefore two key approaches apply 1) low cost single use small mobile robots or 2) sophisticated systems to tackle unique challenges. This offers challenges with respect to offering reliability at a reasonable price for maintenance [127].

In 2022, it was discovered that the Boston Dynamics SPOT robot could withstand 413 Roentgen Equivalent Man (REM) of gamma radiation without failure which is equivalent to 82 year’s worth (5.04 REM per year) of the annual human worker force dose limited by the United States Nuclear Regulatory Commission. For comparison, the UK limits the effective dose for employees to 20mSv a year where a conversion results in 2 REM per year therefore the robot could technically handle 206 years of radiation (according to UK standards). However, if robots are required to enter hazardous areas they will be very likely to be exposed to higher doses of radiation at a single time than a human would ever be subjected to. It should also be noted that no radiation hardening was employed in the evaluation [145].

Within electronics, Zhu *et al.* utilises a radiation hardened field-effect transistor that uses semiconducting carbon nanotubes as the channel material alongside an ion gel as the gate and polymide as the substrate. The approach was able to achieve a tolerance of 15Mrad at a dose rate of 66.7 rad s^{-1} (where previous silicon-based transistors achieve 1Mrad) [146]. A review of low-power electronic technologies which includes the common methods for radiation hardening of electronics is provided by Prinzie *et al.*. The authors summarise approaches related to layout, circuit techniques and system-level mitigation for Complementary Metal-Oxide-Semiconductors (CMOS) [147]. With respect to robotics, the precise impact of gamma radiation on electronic devices is somewhat random, leading to unpredictable breakdowns in robots exposed to such radiation. While it's possible to construct robots using radiation-hardened components, the available options are limited, and their cost is frequently several orders of magnitude higher than that of standard components [148]. Hence why research to date has aimed to address challenges via low cost approaches.

Bird *et al.* present a small, low cost tracked robot named ‘Vega’, for nuclear decommissioning with the ability to perform teleoperated characterisation operations within a nuclear environment. The robot was designed to CE standards and used a range of commercial-off-the-shelf sensors for performing inspections. The individual components were radiation tested where some components failed immediately at a given dose and other gradually failed over time. Vega demonstrated resistance to damage at a minimum absorbed dose of 82.6 Gy, aligning with existing literature findings. This surpasses the specified requirement of functioning in a high dose rate environment (2 Gy/h for 8 h), resulting in a total ionising dose of 16 Gy. As a result, Vega could potentially operate within a reactor's identified hot-spot for up to 41 hours [149].

2.3. Robotics

Industry within the ORE sector, academia and government agencies all envision RAI as an enabler to transform many current methods and procedures [76,150,151]. Robotics has made significant improvements within manufacturing and automotive sectors to improve efficiency in production accuracy and number of items produced each day to meet demand [152,153]. In addition, it ensures that staff members have access to the correct information about any plant at the right time to reduce the risk of downtime, and that information can be accessed from a wide range of systems at a centralised point. This can be mainly attributed to Industry 4.0 where computers, equipment, applications are interconnected [154].

Significant danger and hazards are inherent to the offshore wind sector, however, the design and development of autonomous systems will enable significant advancement in robotics as a service across several industries. Automotive, logistics and manufacturing are among the early adopters of robotics, where many of the key learnings from these sectors will continue to be implemented, leading to accelerated growth for the offshore and nuclear sectors. This will lead to robotic systems which are superbly positioned to adapt and upscale system manufacturing to minimise costs whilst global growth for wind turbines increases. For instance, the execution of remote inspection operations on offshore facilities by robotic systems will necessitate the cooperative efforts of diverse robotic platforms. This ensemble includes aerial robots, crawlers, autonomous surface vessels, and autonomous underwater vessels. This trend is irrespective of whether the economy and perception of the nuclear sector leads to a rise or fall in nuclear reactors globally. One thing that will not change is the long durations it takes to decommission these facilities. Sellafield Ltd expect the decommissioning of their nuclear facility to be continuing for another 100 years, where the site is rated as the highest hazard nuclear facility in Europe with the largest inventory of untreated nuclear waste globally [155,156]. Therefore, we expect to see a rise in robotic platforms to improve safety, however, these will require significant testing ahead of regular deployment to ensure trustworthiness [157].

With respect to global service robot trends, 41% represents autonomous guided vehicles resulting in the largest portion of all units sold [158]. Autonomous guided vehicles are the earliest developed robots to date due to their developments from radio-controlled cars into larger vehicles with the ability to overcome most flat terrain; indoor or outdoors. This early research led to robots becoming well established in non-manufacturing environments, conducting tasks within logistics and many manufacturing settings. Inspection and maintenance robots represent the second largest category of all units sold and can comprise of expensive custom solutions to small low-priced products depending on the use case. Defence applications account for around 5% of the total service robots sold in 2018 where the most purchased included aerial vehicles [159]. Figure 2-11 highlights the expected and increasing trend of service robots being employed as tools across various domains. The relatively slow adoption of service robots within the defence sector indicates the more stringent nature of their regulatory framework and protocols. This is due to the sensitivity of hardware, software and assets, highlighting the requirement of fully trusted autonomy and secure robotic platforms however, typically the defence sector has significant financial backing. For example, Anduril, a defence technology start-up raised $1.5 billion

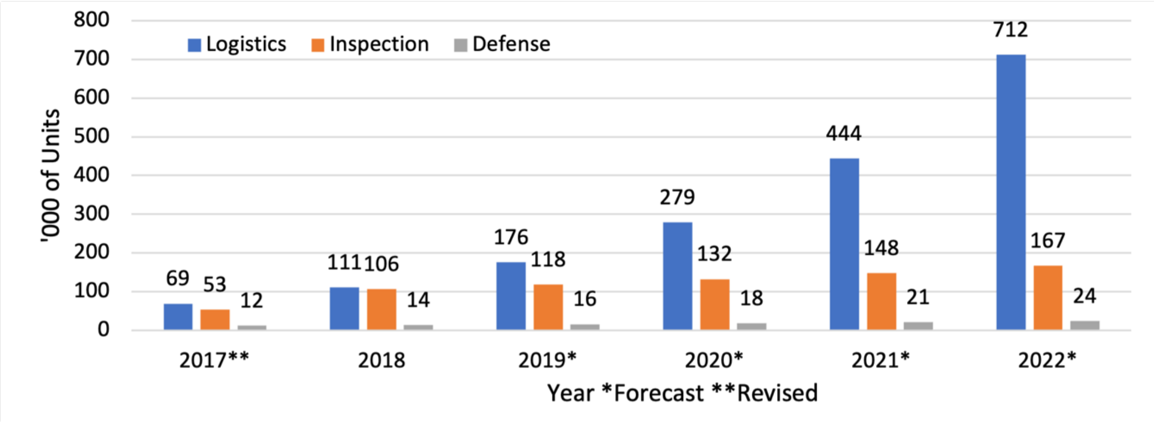


Figure 2-11 Service Robots for industrial applications [158].

with a $8.5 billion evaluation in December 2022. Anduril designs software and hardware enriched with artificial intelligence and machine learning specifically for the military and defence industry. The company collaborates with the UK and its allies to develop drones, underwater vehicles, and various operating and control systems. With a commitment to innovation and state-of-the-art technology, Anduril contributes to improving the capabilities and effectiveness of defence operations [160].

2.3.1. A Survey of the Academic Database

Scopus, a citation and abstract database operated by Elsevier, encompasses nearly 36,377 titles from around 11,678 publishers. Among these, 34,346 are peer-reviewed journals in high-impact fields. Scopus was used to evaluate the ORE and nuclear sectors respectively with the aim to identify current need for robotics in the field. An evaluation of how many publications are relevant to the ORE sector can be taken to represent the future emergence of energy and robotics in the sector. Secondly, a similar search was performed replacing the offshore renewable energy sector for the nuclear sector as a search term. Development and growth in both sectors will result in improvements which are transferrable to a host of sectors. By targeting the offshore renewable energy sector and nuclear sectors, this aims to identify the knowledge and capability gaps which exist across the fields. The approach to the keyword search is presented in Figure 2-12.

An investigation in the research field was first conducted to identify the current needs of the ORE sector and nuclear sectors respectively. This enables gaps to be identified requiring further research focus. Using the methodology highlighted in Figure 2-12, we observe an increasing trend in robotics publications for both sectors.

To identify the focus of these organisations and other academic institutions, an investigation of academic papers published in the ORE sector has been completed. This identifies areas considered as gaps which require further research focus. The search method firstly included ‘ORE AND Robot’ and ‘Nuclear AND Robot’ with searches from 2008-2023. ‘ORE and Robot’ produced 1693 documents found within Scopus where a steady increasing trend can be viewed within Figure 2-13 and respective keywords displayed within Figure 2-14A. It should be noted that ‘Wind Turbine’ and ‘Wind Turbines’ were similar keywords and so the values were merged. The most popular keywords selected by authors of published papers within Scopus for ‘ORE and Robot’ included ‘Wind Turbines’, ‘Wind Power’ and ‘Offshore

Oil Well Production. Although offshore oil well production is not a renewable source, there exists a natural convergence in the robotic technologies applied in both the ORE and Oil and Gas sectors therefore the same robotic platforms are likely to be easily adapted to be applied to both sectors. In addition, Figure 2-14B illustrates three of the leaders for published articles including China, the United States and the United Kingdom. China has positioned itself strategically to optimise the export of offshore wind turbines, benefiting from government support for local developers and the establishment of a growing local value chain. By 2025, substantial growth is anticipated. As part of this initiative, the Chinese government has transitioned from an energy unit set price to a guide price (not exceeding 0.8 yuan per kilowatt-hour), introducing competitive tariff structures for newly approved projects [161]. These policies have positioned Chinese manufacturers, including MingYang, Envision, and

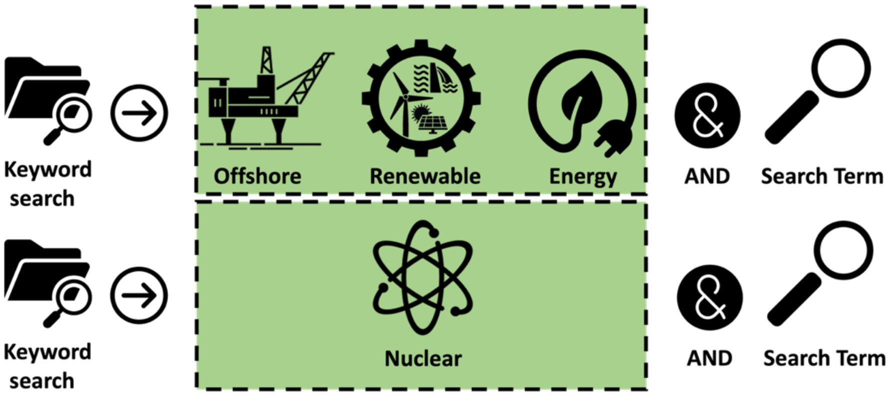


Figure 2-12 Keyword search methodology for Scopus.

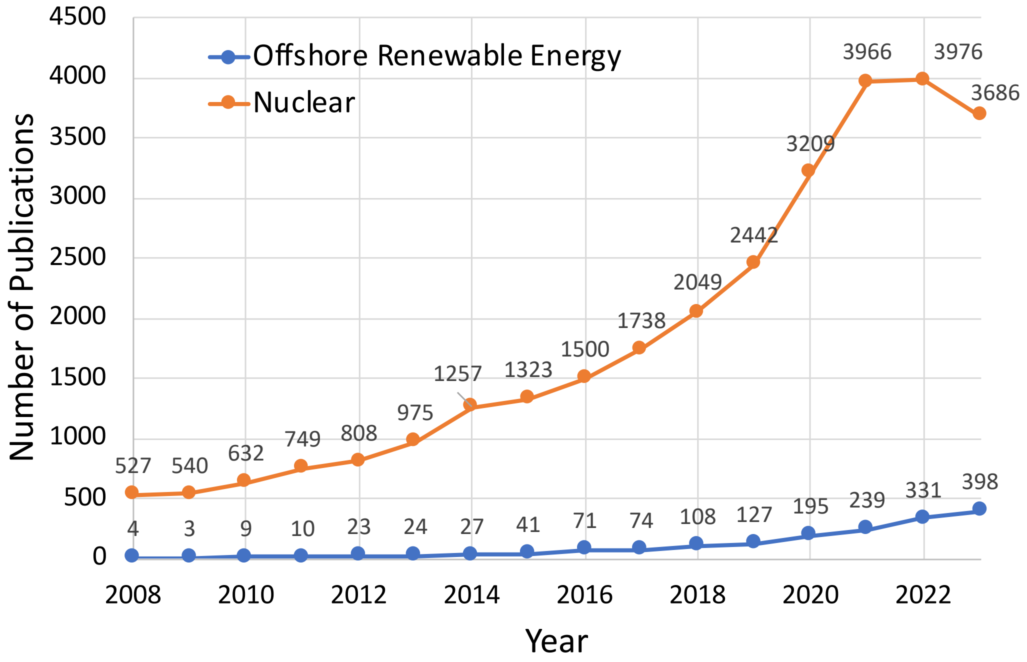


Figure 2-13 Number of Published documents by year in the ORE sector and nuclear sector that contain the keyword robot (Data collected December 2023).

Goldwind, in robust economic positions. According to Rystad Energy, the forecast indicates a sixfold increase in installed offshore wind capacity in Asia by 2025, reaching 52GW [162]. China is expected to contribute significantly, accounting for 94% of the total Asian capacity. The anticipated growth can be attributed to the recent expansion of wind turbine construction manufacturing in China, and it is projected to align with the installed offshore wind capacity in Europe by 2025 [163].

Analysis of the terms ‘Nuclear and Robot’ displays a significantly increased trend when compared to its counterpart with 29,508 documents found within the search across the same timeline within Figure 2-14C. This is identified due to the nuclear sector having gained traction much earlier where for example, the first nuclear reactor was commissioned in 1954 in Obninsk whereas the first commissioned offshore wind farm was only built in 1991 (Vindeby, Denmark) [164,165]. Therefore, the identification of the challenges of radioactive materials in the nuclear sector have been identified for longer therefore Nuclear is ahead of the cycle in terms of use cases for robotics due to improved awareness. It is expected that the ORE sector will have a similar increasing trend in the next 5-10 years. The key search terms for ‘Nuclear and Robot’ is also presented in Figure 2-14C where the top three terms include ‘Human’, ‘Nuclear Magnetic Resonance Imaging’ and ‘Robotics’. Within the key search terms identified it was found that the terms ‘human’, ‘male’, ‘adult’, ‘female’, ‘aged’ and ‘middle aged’ are all very similar therefore they were merged under the term human. It is likely that the reason for this is to understand the differences in radioactivity with respect to different humans where investigations can be found [166,167]. The term article was also omitted from the keyword search as this is typically a common word used in the abstract to introduce the article and resulted in 6587 publications. The United States of America (USA) has the most publications related to Nuclear and Robot within the search. In October 2023, the World Nuclear Association outlines that the USA holds the position of being the largest global producer of nuclear power, contributing approximately 30% to the worldwide generation of nuclear electricity. In 2022, the country's nuclear reactors generated 772 TWh. The inflation Reduction Act was introduced in August 2022 with the aims to provide support for existing and new nuclear development through tax incentives and investment for both large and newer reactors alongside high-assay low enriched uranium and hydrogen production. Within 1992 to 2005 competition in investment was created between new gas-fired plants, and new nuclear and coal-fired plants. At the time coal and nuclear supplied around 70% of US electricity and provided substantial price stability. Investment in these two technologies then nearly disappeared resulting in unsustainable demands on gas supplies resulting in prices quadrupling and forced large industrial users to utilise offshore energy. This change also pushed gas-fired electricity costs towards 10 ¢/kWh. With the advent of shale gas, costs are much lower today [168].

The primary factor driving investment towards gas-fired plants was the lower investment risk they presented, as uncertainties and capital-intensive nature deterred investment in new coal and nuclear technologies. Approximately half of the United States' generating capacity is aged over 30 years, and substantial investments are needed in transmission infrastructure. This led to an acknowledged energy investment crisis in Washington. Simultaneously, there was a growing bipartisan consensus on the strategic significance and environmental advantages of integrating nuclear power into the energy mix. The Energy Policy Act of 2005 subsequently served as a vital catalyst for investing in electricity infrastructure, notably in the realm of nuclear power. Construction of new reactors commenced in 2012, with two units at the Vogtle nuclear power plant and two units at the Summer nuclear power plant, although it is noteworthy that the Summer plant was subsequently cancelled shortly after [168].

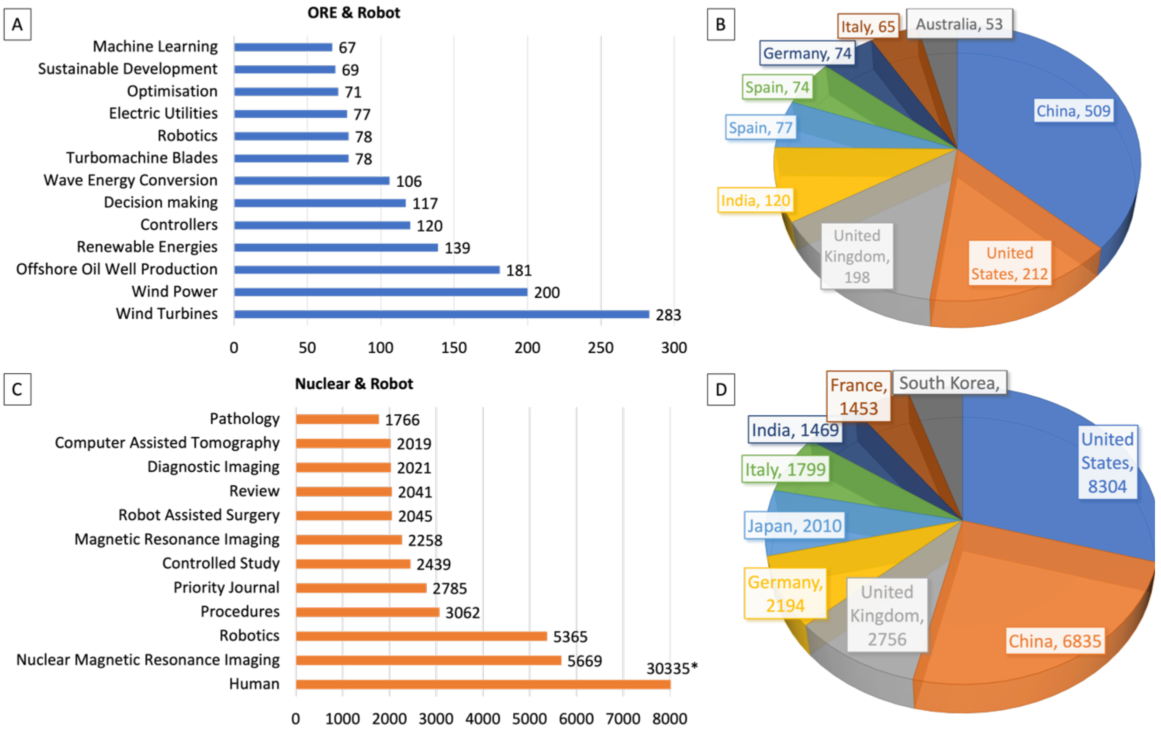


Figure 2-14 A List of keywords for ORE and robot with number of documents published by country presented in B. C List of keywords for nuclear and robot with number of documents published by country presented in D. In C, the exceptionally large bar has been cropped and is marked with an asterisk along with its corresponding value to indicate its significance. (Data collected December 2023).

To identify the primary tasks of robots for ORE and nuclear sectors the keyword search methodology was extended to include an additional term ‘Energy Sector AND Robot AND Application’. Where Energy sector can only be ORE or Nuclear and Application included control, mapping, navigation or IMR. The results for the ORE sector are displayed in Figure 2-15A and nuclear sector in Figure 2-15B. In both sectors, control emerges as the predominant focus of research, attributable to the shared necessity for the development of robots capable of navigating hazardous environments and confined spaces. This demands the design and manufacturing of robots that not only fulfil these specific requirements but also exhibit enhanced manoeuvrability. Within the nuclear sector, the second most prevalent research theme revolves around mapping, likely stemming from the initial challenge posed to robotic engineers by the nuclear industry. The imperative of mapping is underscored by the need for engineers to regularly inspect facilities and identify any alterations. In the ORE sector, the subsequent most significant research topics, maintenance and inspection, closely contend in terms of the number of published articles. These areas are likely prioritised due to the operational and maintenance challenges faced by many ORE facilities, necessitating human-led inspections and maintenance on offshore platforms enduring harsh environmental conditions. Consequently, the emphasis on inspection and maintenance reflects their critical importance in ensuring the optimal functioning and longevity of ORE installations.

From this subsection presently, applications of robotics primarily focus on supporting short-term objectives in operations and maintenance procedures. Nevertheless, looking ahead, robotics with respect to the ORE sector holds the potential to significantly impact various aspects throughout the entire spectrum of the lifecycle of offshore wind infrastructure, from surveying, planning, design, logistics, operational support, training and decommissioning, and have significantly similar roles within the nuclear sector [20]†. For the nuclear sector opportunities exist primarily for operation, maintenance and decommissioning of facilities to reduce radiation risk for humans and improve overall inspection results. Both sectors share the same overall goals in terms of ensuring safety in hazardous environments and increasing plant knowledge about their facility where lessons will be shared bidirectionally as more robots are adopted. Whilst, currently, the nuclear sector has more publications produced with respect to robotics and nuclear applications, the author expects that robots will more regularly be deployed sooner within the ORE sector when compared to the nuclear sector as nuclear applications face challenges in terms of ensuring that robotics can operate consistently in the way it is intended as a minor failure onboard a robot can lead to a major catastrophic incident to take place. By contrast, although errors on robots within the ORE

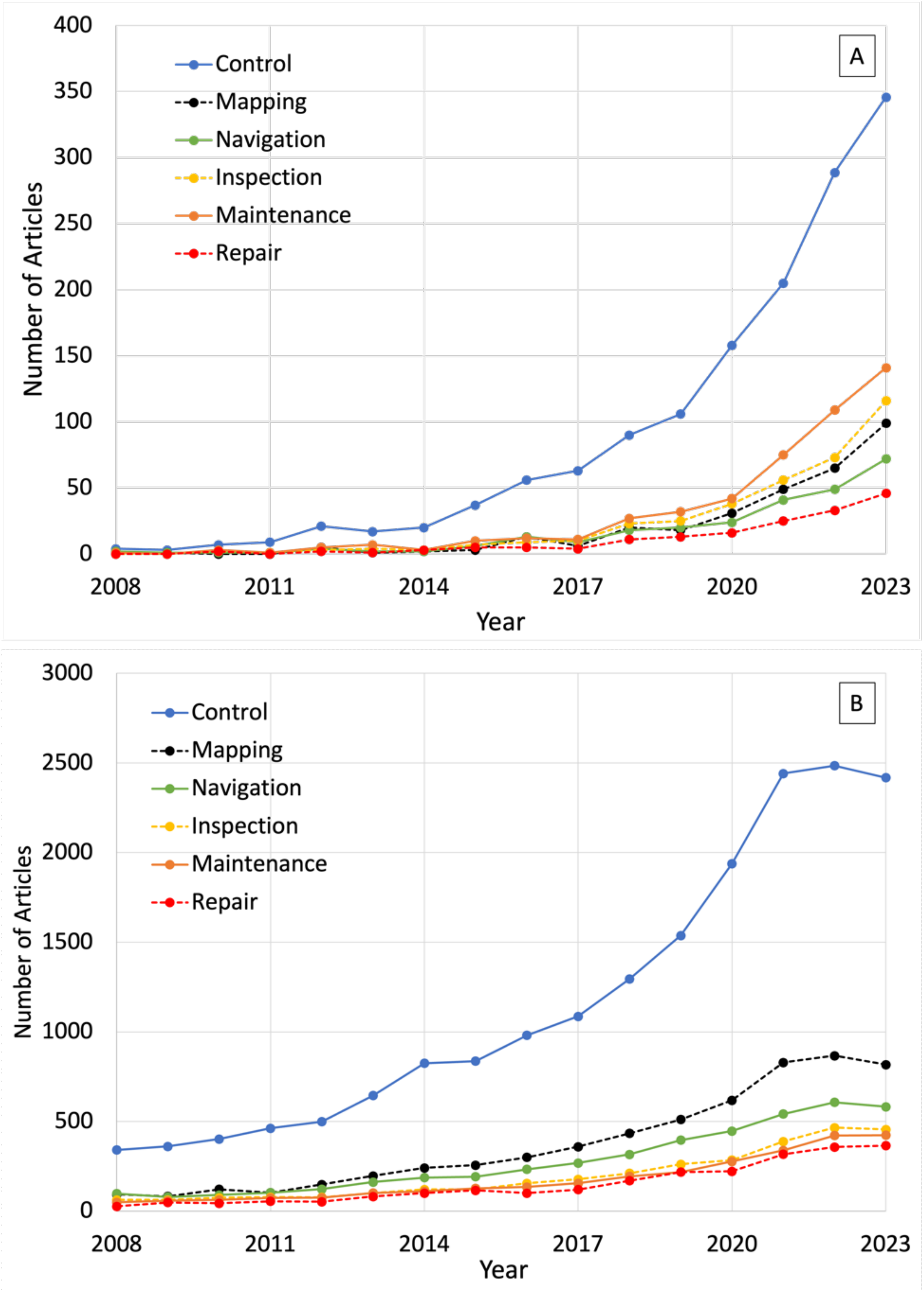


Figure 2-15 Summary of papers for application with respect to sector and robot A. ORE sector and B. nuclear sector (Data collected December 2023).

sector, may lead to damages offshore, they do not lead to issues which can cause global catastrophe. This helps to explain why the nuclear sector has a slower and more difficult adoption rate to overcome.

2.4. Chapter Summary

This Chapter highlighted market trends for both the ORE sector, nuclear sector and Robotics sector highlighting trends with respect to the sector and robotics with respect to the specified sector throughout. In addition, a Scopus keyword search was conducted to identify the areas and challenges which academia has identified via number of publications.

In summary and in sequence as keypoints appear in this chapter, the ORE sector is expanding. More specifically, offshore wind farms are being installed further away from the shoreline and being manufactured larger to capture higher wind speeds offshore. This has been mainly due to goverments providing incentives to companies in this sector to ensure that countries can adhere to the Paris agreement. Therefore to minimise costs and ensure the efficiency of offshore infrastructure, robots will be instrumental in ensuring frequent and rapid inspections when systems fail or are damaged and rapid repair to reduce the downtime of assets. There is also still challenges in creating a sustainable lifecycle for offshore wind farms as, to date, at the end of a wind farms lifecycle they are simply burried in landfill. Whilst some companies do exist in recycling the materials there is issues in scaling and breaking down the materials to make this process more efficient.

While the nuclear sector in the UK is currently downsizing, many regions globally are expanding their nuclear energy capabilities. This growth is largely driven by public perception of nuclear power as a clean energy source; however, there is often limited awareness of the challenges associated with nuclear energy, such as difficulties in material storage and the potential for global catastrophes in case of failures. For roboticists, the challenge lies in assuring nuclear operators that their robots can consistently perform inspections and manipulation activities without failure. Current case studies indicate that robots could address tasks such as regular inspection monitoring and inspections in underwater storage tanks to manage the inventory of nuclear waste. As decommissioning processes often require extensive time, robotics becomes crucial, particularly in minimising human exposure to dangerous radiation. Nevertheless, a challenge remains in ensuring the sustained value of reliable robotics and autonomous systems which encourage trusted persistent deployments for a human operator.

Robotic systems provide several opportunities to optimise current procedures, overcome challenges with respect to IMR activities such as improved analysis, more frequent analysis and increased information about a facility via interconnected systems and computing. However, one of the key contributions when concerning ORE and nuclear sectors is to improve the safety of its workforce whilst improving the quality of inspection. The 5D's of robotisation are well reported where robots are able to overcome the challenges of dull, dirty, dangerous, dear and difficult jobs. Moreover, unlike nuclear facilities situated on land and in close proximity to civilisation, offshore facilities are being positioned farther out at sea, making it challenging for companies to recruit a workforce willing to work offshore, away from their families. This underscores another advantage of robotics in addressing the workforce commitment issue [169,170].

3. Background Reading

For the purposes of this thesis, it is important to properly define autonomous mission evaluation, resilience and reliability. For example, Zhang *et al.* define resilience as associated with a system and the ability to recover function due to damage on the system. However, advancements in different functionalities and AI of robotic platforms over time has resulted in the omission of new resilience requirements which is attributed to more advanced missions, and complex environments [171]. Robotics often misinterprets resilience and reliability. Reliability prevents system damage, while resilience deals with system recovery. They achieve similar outcomes but stem from different causes and aren't interchangeable. Our new key definitions are discussed below:

Autonomous Mission Evaluation – The ability to independently formulate and decide on the optimal course of action for a robot or autonomous system to complete based on the specific goal from a HITL based on its independent understanding of the environment, system knowledge, robotic capabilities, limitations and given situation. The mission is overseen and evaluated by the HITL supervising the system typically evaluating against key measurands which may be quantitive or qualitative.

Resilience- The ability for a system to recover from or adjust to misfortune or unforeseen circumstances [171]. Thus, from the perspective of safety compliance and robustness, resilience enables a robot to survive and remain operational irrespective of adversity, thereby maximizing the rate of mission success..

Reliability- The act of monitoring and ensuring the operations of onboard systems including mechanical parts, components, electronics, software and onboard sensors with the aim to reduce risk of failure and maximise the health of the robotic asset lifecycle, hereby, increasing the mean time to failure [172,173].

3.1. Cyber Physical Systems

There are several areas of robotics which require improvements to advance their speed of deployment [174–178]:

- Trust that a system can act as intended
- Ability to remotely control robots from a safe distance
- Efficiency in the communications across long distance

- Visualisation of results from the perspective of robots translated to a human operator.

Cyber-Physical System (CPS) is a term which has emerged due to a trend and requirement for significant interconnectivity across embedded systems deployed in the field (sensors, actuators and robots) with computation technologies (simulations, dashboard interfaces and digital twins), where an overview of CPS is displayed in Figure 3-1 [179,180]§. A CPS can be described as a complex system with natural integration and comprehensive collaboration of computation, communications and control technology [181]. It is important to emphasise that CPSs differ from wireless sensor networks and Internet of Things (IoT) for the following reasons. Wireless sensor networks only conduct the sensing of the signal and do not necessarily detect and differentiate between the specific signal and several objects being sensed [182]. CPS provide the data support and provides the perception for a wide range of specific applications through data collection, integration, processing and routing. IoT simply connects sensing devices via the internet such as wireless networks and Radio Frequency Identification (RFID) and completes overall perception, reliable transmission and intelligent processing of data. IoT tends to only implement simple perception and simple control [183]. By contrast, a CPS can sense and has a strong ability to control the physical asset and is a credible, scalable and controllable network of physical equipment that merges the ability of control, communication and computing through feedback loops of interaction. The interactions include a combination of calculations and physical processes, deep integration and run-time interaction to extend existing functions to ensure the physical asset can be detected, operate and be controlled in an efficient, safe and reliable way [184].

CPSs are significantly complemented by Digital Twins (DTs) which can result in improvements in control via simulations. A DT can be described as a copy of a physical asset, environment and/or system that is connected to a digital asset of the same environment to visualise and interact with shared operational data [185]. The cyber and physical segments of CPSs have had accelerated development in recent years mainly attributed to improvements from physical attributes of robotic platforms [20,186,187]† (also discussed in Chapter 4), improved computation durations and processing (i.e. Intel & Nvidia processors), digital modelling [188–190] and wireless connectivity including developments in the internet of things [191,192]. However, there do exist bottlenecks in the most optimum approaches to synchronously bring these technologies efficiently together with bidirectional communications across HITL, DT, robotic systems and sensors under a CPS. The motivation of this thesis seeks to overcome these issues via a symbiotic approach

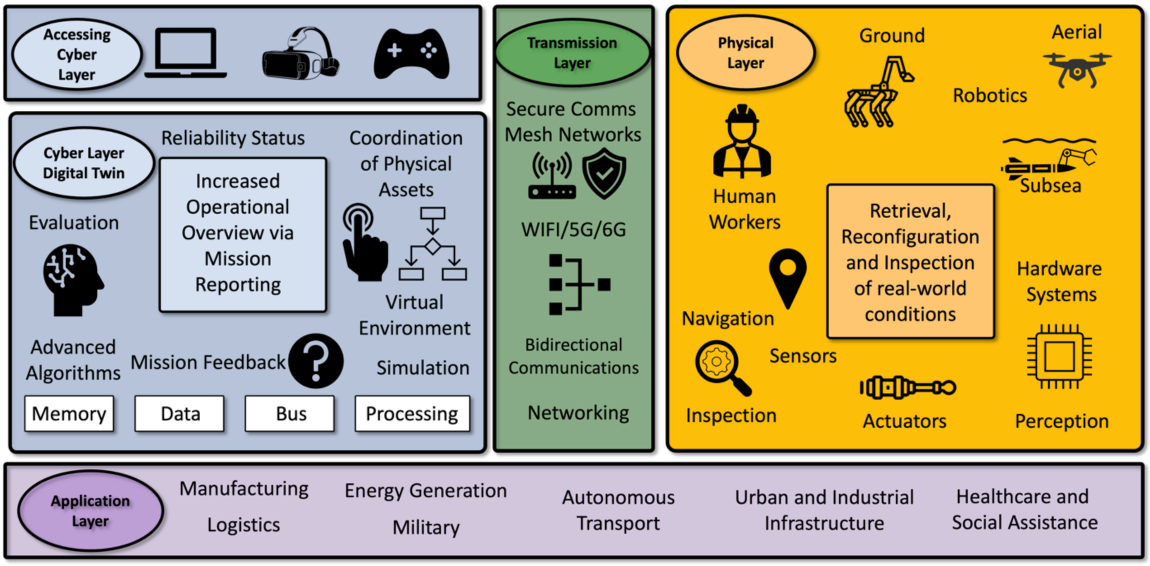


Figure 3-1 A summary of key elements required in a cyber physical architecture alongside important examples.

where robots can utilise bidirectional communications to operate symbiotically as a team within an inspection mission.

It is important to note at this point that different definitions of DTs exist where often other DTs present a mirror of an asset in the simulated environment. For example, a digital shadow can be considered as the real-time digital representation of a physical asset with communications in one direction, resulting in the data from the physical asset being represented in the virtual asset. A change of state of the physical asset leads to a change in the digital asset but not vice versa [193]. To re-emphasise, a DT features these two-way communications where the physical asset can be reflected in simulated asset and the simulated asset can result in the adaptation/influence of the physical asset to improve operations and the physical asset can also inform on the simulation variables.

3.2. Other Important Areas of Research Considered

Whilst a CPS features a wide range of systems, sensors, actuators and opportunities for a human to interact, there are also other areas which are essential to the trusted, safe, resilient and regular deployment of robotics and autonomous systems.

3.2.1. Safety

Safety is considered as the most important feature when deploying a robotic platform. There are many different features which are required for robotics to consider them as safe for deployment. These can include robots which operate safely around humans [176,194,195], within different environments (such as dangerous or confined spaces) [196–199], and/or in collaboration with other robots [200–202]. However, safety can extend further than just physical devices to trusted deployment of software such as within DTs. For example, can a human trust from a digital interface that the simulation of a robot matches the physical robot [203,204]. This becomes especially important as robots operate BVLOS, handle dangerous objects and access dangerous areas.

3.2.2. Cybersecurity

As the adoption of all technologies increases in various sectors, the demand for robust cybersecurity also increases to ensure the safety of assets and information. An acceleration in opportunities in cybersecurity have mainly been attributed to the creation of the IoT via smartphones, laptops and other digital devices. The more devices that a person connects, the more risks that are faced with respect to the person and network and the higher cybersecurity risk to global infrastructure [205]. These technologies have become fundamental to everyday activities therefore, if these systems do not have thorough cybersecurity, they could malfunction via failure or hacking and significantly affect societal demands.

The regular and trusted implementation of robotics within infrastructure systems requires stringent cybersecurity to be in place ensuring the resilience to malfunctioning errors and protection from malicious attacks [206]. As more infrastructure such as energy facilities (offshore, onshore and nuclear) realise and utilise the benefits of digital technologies, this also increases risks to malicious attacks. This too includes the increases in robotic technologies which are being more regularly deployed to inspect and maintain these facilities. Effective cybersecurity must ensure secure information gathering as well as the security of the robotic assets themselves as malicious attacks could lead to devastating results which could heavily impact human life [206,207].

Robotic cybersecurity includes several areas which are presented in Figure 3-2 which discuss areas that can be exploited or act as vulnerabilities. Issues exist within a range of cybersecurity systems due to problems which may not be recognised or identified yet. This can be due to weak networks, poor design and the absence of human-machine collaboration. Vulnerabilities typically include areas with weak defence often resulting in poor overall system performance and are usually solved via system updates. Threats within CPSs are a

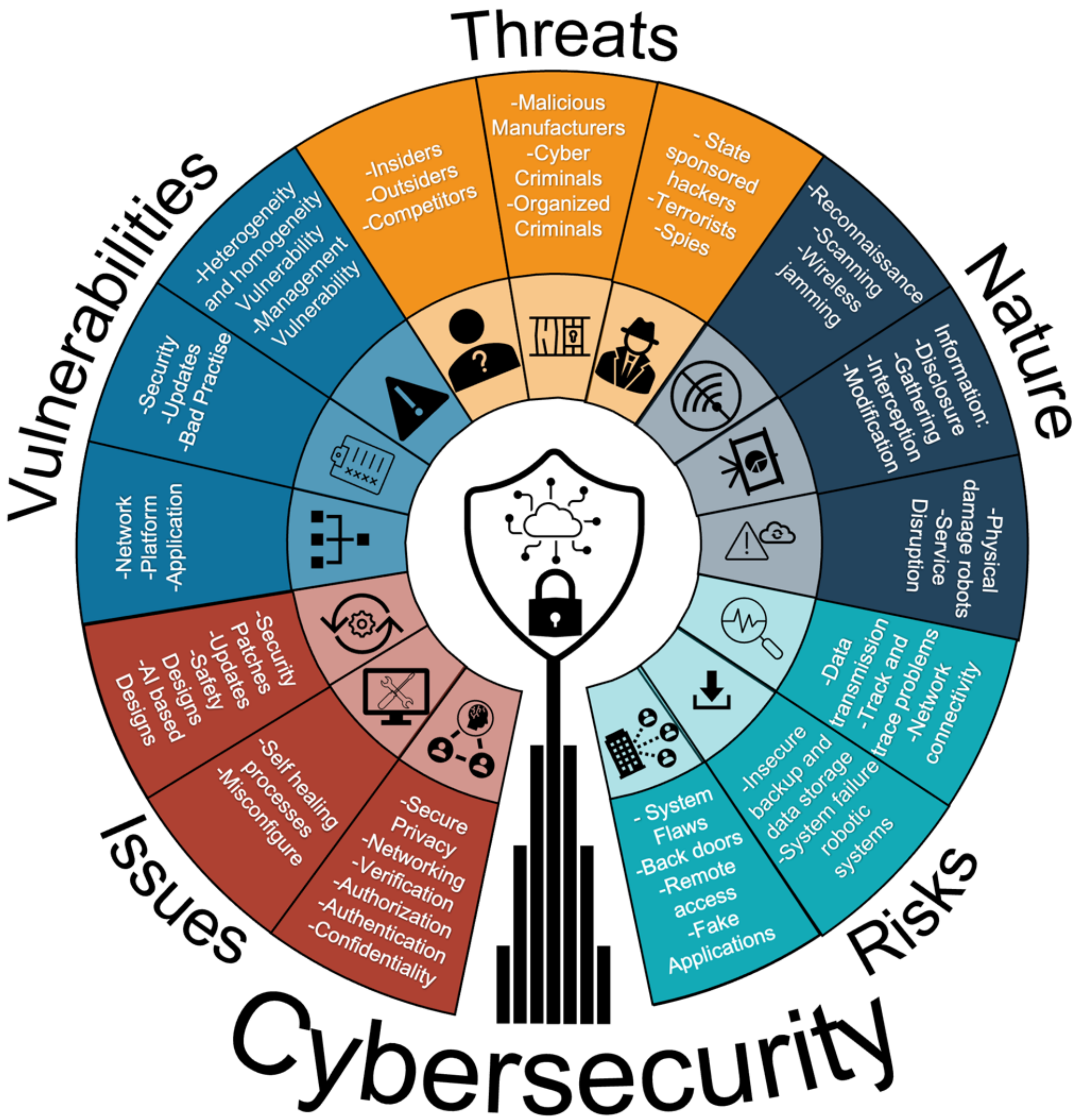


Figure 3-2 Key elements to be considered when ensuring robust cybersecurity.

growing concern with the state of global politics and need to ensure resilient supplies of energy for countries. This is of concern due to data theft via malicious attempts to cause detriment to a system. This does not necessarily just include hacking from outside of an organisation and can include insiders, competitors and outsiders [208].

Essential levels of protection can be provided from blockchain technology where these risks can be minimised via smart algorithms implemented on a custom Ethereum blockchain, which can record each robot’s estimate, can filter out suspicious estimates which highly deviate from the mean and computes the aggregated estimate of the robotic swarm [209]. This can be useful when a swarm is deployed to scan an area several times, however, poses different challenges for robots in confined spaces where a swarm may be unable to navigate. This would mean a robot would be required to accurately detect and inspect correctly first time every time and scans could not necessarily be filtered out in the presence of a malicious attack. Other forms of cybersecurity will be crucial to the delivery of robotics to ensure that they are trusted to be secure, the risks as displayed in Figure 3-2, especially as they are required to inspect and maintain more infrastructure which can become dangerous such as in nuclear.

3.2.3. Standardisation

The challenge of standardisation is an area which inhibits the acceleration of scalable robotic systems and AI especially within a CPS approach. However, it must be noted that there is a need for development of standards with respect to a host of key areas in robotics which ranges through ethics [210,211], wireless communications [212–215], ontologies [216] and resilience [217].

A summary of standards for swarm robotics including communications, hardware, sensors, tasks and localisation systems was provided by Nedjah *et al.* [218]. As robotic fleets become more heterogeneous and larger, it will be vital to ensure a standard so that robots can be seamlessly integrated within a system of systems approach, especially as robots currently all utilise different programming languages and/or proprietary systems [219–221].

Reliability is an important concept which currently does not have any standards for detection and diagnosing issues. For example, a robot may be certified as safe to use out of the box however, but may not undergo regular inspection and maintenance of the physical systems and software which is overseen by a body to ensure certification; similar to how a car undergoes an MOT. There are also differences in the definitions of reliability. For example, Zhang *et al.* define reliability for a robotic manipulator as the probability of occurrence that the kinematic error is less than the error tolerance. However, this thesis would define the reliability of a robotic manipulator as the ability for a robotic arm to undergo tasks until it requires maintenance or fails. The key differences include where Zhang relates reliability to accuracy and this chapter relates reliability to the failure of a robot however, we do agree that an inaccurate robotic arm would therefore require maintenance.

3.3. Top-Down versus Ground-Up Approaches

Within robotics, there are two common approaches which lead to the optimisation and deployment of robotics. These consist of two key approaches outlined in this segment of the thesis and are important to differentiate between when discussing the concepts in the discovery and design of the symbiotic approach presented in Chapter 5 onwards. An example of *ground-up versus top-down* approaches to robotics is presented within Table 3-1 and Table 3-2. The two different methodologies can be used in various contexts such as software development, problem solving and project management, where the approaches differ in starting point and how they proceed to achieve their goals. The ground-up approach commences with the most fundamental components and builds up from there. This leads to progression where complexity increases and finally a detail-orientated segment to focus on understanding the components and their interactions before moving further. A top-down

Table 3-1 An overview of a *ground-up* approach to robotics.

Stage	**Description**
Starting Point	Fundamental building blocks of robotics- Sensors, actuators and control algorithms
Progression	Assemble building blocks to create a robot requiring mechanical structure, integration of sensors, develop low-level control software and adding high-level functionalities
Detail-oriented	Ensuring a detailed understanding of the robots hardware and software components, ensuring the function correctly and moving onto more complex behaviours
Example	Design and manufacture of a robot including custom chassis , writing code and implementing high-level functions such as navigation and image processing for object recognition

Table 3-2 An overview of a *top-down* approach to robotics.

Stage	**Description**
Starting Point	Start with high-level task you want to accomplish such as autonomous navigation
Progression	Break this down into subtasks and components. E.g. autonomous navigation would require obstacle avoidance, path planning and motor control
Abstraction	This is used to simplify complex robotic tasks where you may use high-level programming languages, predefined libraries or existing frameworks
Example	Using an off-the-shelf platform to create a robot vaccum cleaner (the robot already functions) so we just need to create the subtasks such as obstacle avoidance and floor cleaning to achieve the goals.

approach follows a similar approach in terms of starting point, progression and abstraction where it commences with the overall view or high-level concept which is then broken down into smaller segments to achieve the goal. Progression occurs with close reference to the broader perspective where iterative refinement occurs along this segment. Abstraction then typically occurs to simplify the problems further.

Within this research, MR-fleets are presented therefore an example of previously discussed topics in this chapter are presented within Figure 3-3 where the top-down approach is summarised as human facing features and robotic features [9]†. Within the diagram, key similarities in the layers of the approaches are also summarised as function, autonomy, communication and validation/verification layers. This is important to recognise as the aims of objectives for robotics remain the same in terms of progress and advancement however, important to appreciate the difference as this research mostly focusses on the top-down approach with respect to resilience, reliability and safety.

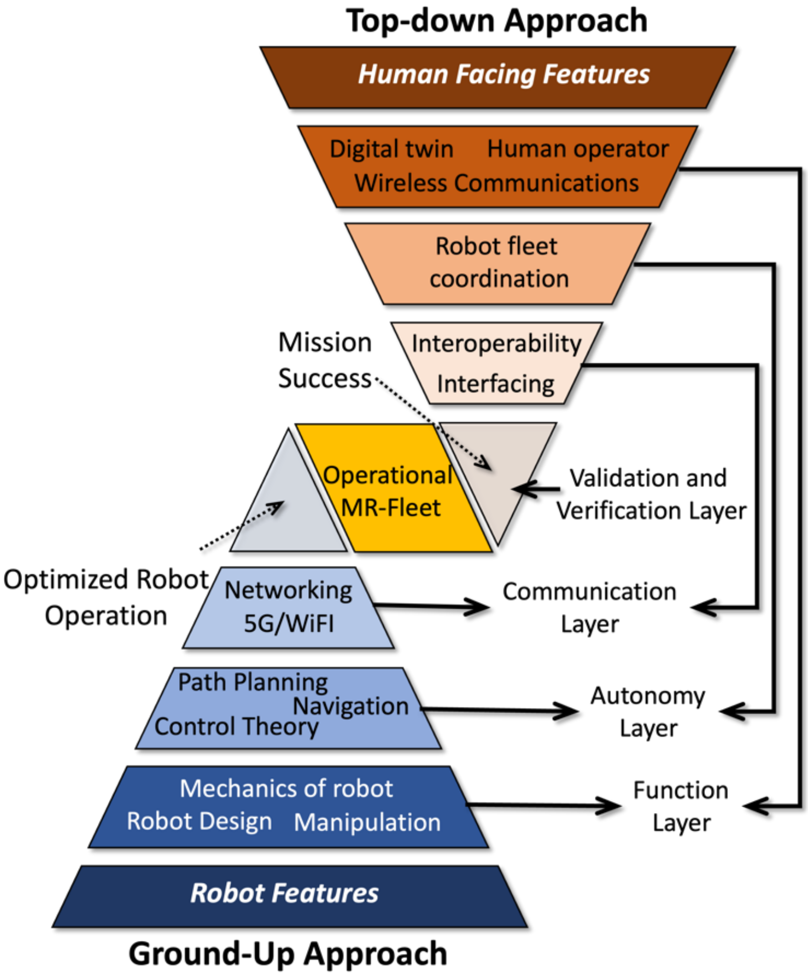


Figure 3-3 The differences and similarities between a top-down and ground-up approach [9]†.

4. State-of-the-Art Literature Review of Individual Mobile Service Robots and Multi-Robot Fleets

With the trend of demand for robotic IMR growing in both nuclear and offshore energy sectors, and with distributed case studies of how robotics and artificial intelligence can enhance IMR at different stages of the lifecycle of an asset. It is important to conduct a detailed review which undertakes both ground-up capabilities of robotic platforms and top-down reviews of multi-robot fleet management interfaces using both industrial and academic sources [222]†. This chapter provides quantitative and qualitative analysis of key research activities and outputs alongside expert analysis over the last 5-10 years. Key takeaway points from this review include significant advances in autonomy acting as key enablers for several commercial-off-the-shelf platforms. Whilst the hardware for these platforms had existed for a while, the primary advances relate to the system integration and data analysis from these existing technologies. However, we also identify a bottle neck in the persistent deployment of autonomous systems where a route to autonomy as a service must be taken. Safety and regulation of robotics is also something that must be addressed. For example, robots are often certified as safe from unboxing [223]. However, there is no framework or regulation in place which validates and verifies these systems throughout their remaining useful life. Therefore, the development of quantitive methodologies for self-certification (reliability issues) and resilience issues will be a key metric in key performance indicators in the future of successful deployments. This would significantly drive the roadmap for trusted autonomous deployments in the offshore and nuclear sectors where robots could operate resident to the areas they inspect [224].

The state-of-the-art in mobile robotics has several layers which verify the successful deployment. To date, this has been summarised under a sense, perceive, plan and act approach. Whilst this methodology will remain for the deployment of individual robots, adaptations will be made to ensure the successful deployment of multi-robot fleets, which co-exist and operate more cohesively as a team. This review highlights the current capability in robotics which are regularly deployed within industry, provides analysis of the state-of-the-art in the DARPA Subterranean Challenge, limitations in persistent autonomy and finalises in a discussion of the state-of-the-art in cyber physical systems.

4.1. Ground-Up Capability of Service Robots

To support the analysis of the state-of-the-art in RAI, this section decouples robotic platform type, application and level of autonomy for notable robotic platforms regularly deployed for IMR missions within the offshore and nuclear sector for both academia and industry. The following is highlighted within this section:

- The Spectrum of Autonomy: Various robotic platforms exhibit distinct degrees of autonomy, influenced by factors such as their intended functionality and specific application constraints, such as safety considerations and environmental context. This insight sheds light on emerging patterns regarding autonomy levels, the extent of human involvement or intervention, and the diverse perspectives on autonomy.
- Service Robots in Hazardous Environments: This subsection offers an overview of the existing capabilities of robotic systems, encompassing terrestrial, aquatic, and aerial domains, within the realm of robots which face dangerous environments such as nuclear and offshore.
- Robotics Hype Curve: This facet enables a well-informed examination of the maturity, adoption, and acceptance of robotic platforms in various markets and applications.

4.1.1. The Spectrum of Autonomy

‘Autonomous system’ is a term which is regularly used in both academic and industrial contexts. However, the precise definition varies depending on the specific scenario and application, such as robot type, software, AI, and even within autonomous vehicles. In this context, a comprehensive and reliable autonomous system is characterised as a system possessing the capability to operate autonomously, making independent decisions onboard while adhering to a predefined set of rules that ensure safety, self-certification and an effective mission [176,225]. The levels of autonomy are identified in Figure 4-1 [20,176,225]†.

0 – No Autonomy – A remote control is employed for teleoperating the system. The human operator assumes complete responsibility for ensuring the robot's safe operation, a process that usually takes place either within visual line of sight or remotely via an onboard camera. Although there may be sensors in place to detect potential collisions, akin to parking sensors in automobiles, it remains the human operator's duty to navigate and avoid obstacles.

1 – Operational Assistance – In this scenario the robot is teleoperated again however, there are minor safety features which may consist of collision avoidance via Simultaneous Location and Mapping (SLAM) or automatic emergency stop.

2 – Partial Automation – Semi-autonomous operation occurs within this level where the human is responsible for the robot, however, the robot has the ability to perform some task autonomously when initiated and supervised by the human.

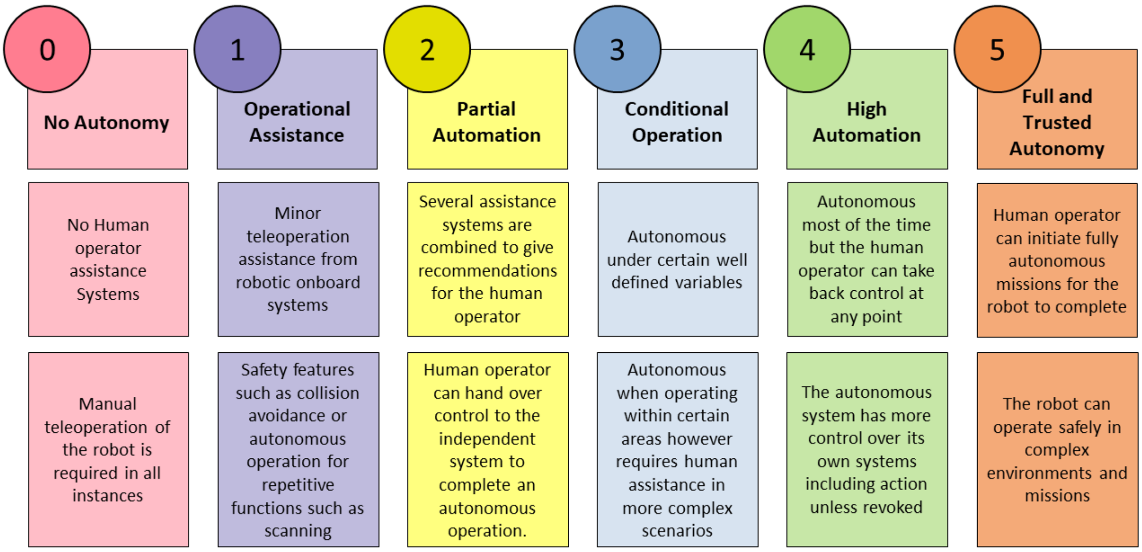
3 – Conditional Operation – The mobile robot performs sufficiently under well-defined variables. This is currently seen in ‘robot only zones’ in warehouses and when autonomous cars operate on motorways due to the likelihood of unpredictable events being reduced.

4 – High Automation – The human has the ability to retrieve control of the robot at any point during a mission however, the robot is fully autonomous in many scenarios. The robot can also provide suggestions for order of tasks and optimisations.

5 – Full and Trusted Autonomy – A robot can be assigned a mission and the robot can ensure the mission is completed in a safe manner. The robot can adapt to unforeseen changes to the mission such as challenges and events, where the robot can make decisions itself or defer decisions to the overarching human.

4.1.2. Field Robotics

In recent years, subsea robotics have developed from surface vessels which tow different sonars for a wide range of different inspections to subsea vessels which are now able to maneuver themselves underwater. For subsea vessels, wireless communication challenges exist due to signals not travelling efficiently underwater due to the communications using



0	1	2	3	4	5
No Autonomy	**Operational Assistance**	**Partial Automation**	**Conditional Operation**	**High Automation**	**Full and Trusted Autonomy**
No Human operator assistance Systems	Minor teleoperation assistance from robotic onboard systems	Several assistance systems are combined to give recommendations for the human operator	Autonomous under certain well defined variables	Autonomous most of the time but the human operator can take back control at any point	Human operator can initiate fully autonomous missions for the robot to complete
Manual teleoperation of the robot is required in all instances	Safety features such as collision avoidance or autonomous operation for repetitive functions such as scanning	Human operator can hand over control to the independent system to complete an autonomous operation.	Autonomous when operating within certain areas however requires human assistance in more complex scenarios	The autonomous system has more control over its own systems including action unless revoked	The robot can operate safely in complex environments and missions

Figure 4-1 The spectrum of autonomy highlighting different levels which currently exist and are considered as autonomy [20,176,225]†.

acoustic waves instead of electromagnetic such as above the surface of water. These robots range from robots with optical cables for command and control of the robots to torpedo based robots which are efficient and save different data onboard to later share with the human when retrieved.

The Hugin Autonomous Underwater Vessel (AUV), displayed in Figure 4-2, is a subsurface torpedo shaped robot which is used to automate inspection processes underwater. The torpedo shape enables the robot to maneuver efficiently through the water enabling for a run-time of 100 hours at 4 knots. In addition, the vessel can be deployed in sea states up to level 5 however, further work is required to ensure the robot can be deployed in harsher sea states which are typically found further offshore [226,227]. At the time of writing this thesis, no indication of case studies or performance factors were released for the Hugin robot. For surveying the seabed, the robot is very useful, however, could be improved with the inclusion of a retractable arm so that manipulation activities may also be conducted in the future [228,229].

I-Tech introduced the Centurion SP, displayed in Figure 4-3, the newest addition to their Robotic Operated Vehicles (ROVs). Specifically engineered for operations in deep-water projects characterised by strong sea currents [230–232], this series of ROVs marks a departure from their traditional usage confined to the Oil & Gas (O&G) sector. The latest iterations of these ROVs are now being employed in the planning and construction phases of OWFs due to their significant advantages outlined in Figure 4-3-left. However, these types of vessels have limitations, including the necessity of a tethering cable for power supply and control, as well as notable constraints in conducting missions within confined spaces.

Hugin AUV		
Application	Key Features	Tasks
Planning	Stability	High Resolution Seabed Mapping
Development	Maneuverability	Geophysical Site Inspection
Maintenance	Battery Endurance: 100 hours at 4 knots	Oceanographic Assessment
Array Assessment	Operating Depth: 6000m	Environmental Monitoring
Lifecycle Stages	Flexible Capacity	Marine Countermeasures

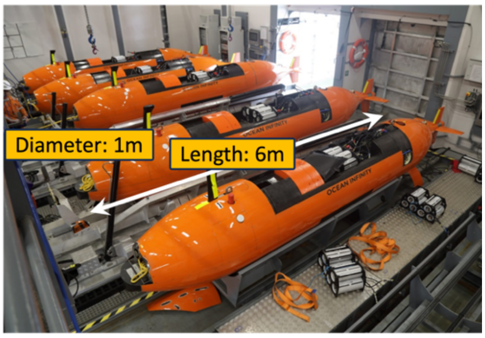


Figure 4-2 Hugin AUV robotic capabilities (left) alongside an image in deployment within its launch platform [226,228,229].

iTech7 Centurion SP		
Application	Key Features	Tasks
Planning	Stability	High Resolution Seabed Mapping
Inspection	Maneuverability	Geophysical Site Inspection
Repair and Maintenance	Powered via tether	Oceanographic Assessment
Asset Integrity	3000m or 4000m ratings	Environmental Monitoring
Production Enhancement	Flexible Capacity	Marine Countermeasures
Decommissioning	8 cameras available in HD with optional 3D video	Debris Clearing and Recovery Support

Figure 4-3 iTech^7 Centurion SP capabilities and key features alongside an image of the ROV in deployment [230–232].

Confined spaces provide several challenges for mobile service robots, however, opportunities exist for robots which travel around permanently installed rail systems. This would be useful for a wind turbine nacelle where it is difficult for compact UAVs to navigate throughout however, a rail system as displayed in Figure 4-4A enables for safe movement throughout the nacelle reducing the risk of damaging equipment within the nacelle. A rack and rail system was demonstrated using a USB camera on a pan tilt unit within a replication of a nacelle [233–236]. The railed system had benefits which included reliable movement, a method to provide power and could include multiple different sensors onboard. Some limitations included the requirement for companies to retrofit or implement these rails into their designs and faults in unforeseen areas were inaccessible due to the rail.

Autonomy does not necessarily have to be limited to robotic platforms. Many large vessels are beginning to incorporate autonomy within their systems such as in the Rolls-Royce Advanced Autonomous Waterborne Applications Initiative (Figure 4-4B) representing one of the most significant investments made in autonomous shipping. A partnership comprising industrial and academic entities has acknowledged that a ship's capacity to self-monitor its condition, recognise and interact with its environment, and make informed decisions based on gathered data is crucial for advancing autonomous operations. The necessary sensing technology for achieving autonomous shipping already exists; the primary challenge lies in devising the most efficient, safe, and cost-effective methodology to integrate these technologies reliably effectively [237].

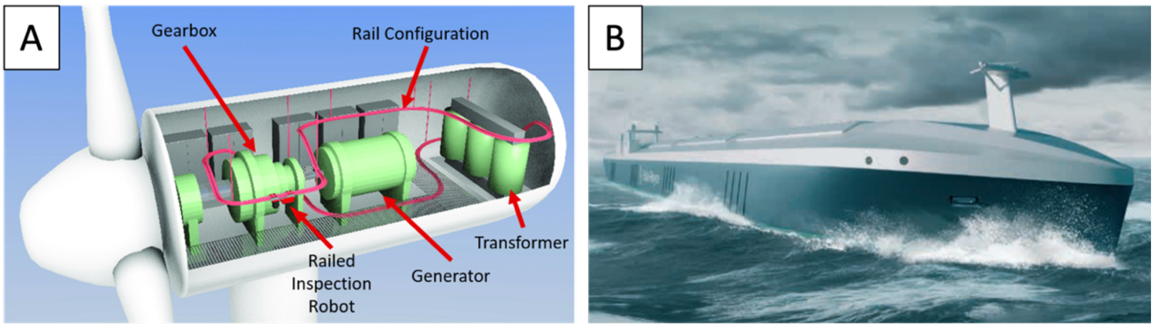


Figure 4-4 A- A proposal for a rail guided robot within a wind turbine nacelle [236]. B- Conceptual image of the Rolls-Royce Advanced Autonomous Waterborne Applications Initiative [237].

Key technical prerequisites for autonomous maritime logistics include:

Sensor Fusion: Integrating radar, high-definition cameras, thermal imaging, and Light Detection and Ranging (LiDAR) within the maritime environment, ensuring reliable and efficient technology integration.

Control Algorithms: Developing mature algorithms for navigation, collision avoidance, and real-time decision-making based on sensor data. Algorithms need to comply with maritime regulations, refined through iterative testing and validation.

Communication and Connectivity: Establishing regulated standards for autonomous ships to coordinate docking and connect to a DT, supporting operational functions and asset health reporting.

Some smaller examples of vessels include an Unmanned Surface Vessel (USV) 'Halcyon' (Figure 4-5A), which was created by Thales where the capabilities of the USV included autonomous operation across the English channel to Plymouth resulting in around 150 nautical miles [238]. The crossing across the horizon aimed to demonstrate the robustness of the USV via its long-range ability for the mine countermeasures boat where a mine countermeasure sonar for high resolution imagery and in water object detection payload can be included [239,240].

The Windfarm Autonomous Ship Project (WASP) presents an integrated autonomous vessel and robotic cargo transfer system designed for spare parts delivery to OWFs. Recognising that vessel and logistics costs constitute up to 60% of OWF operational expenses, with a significant impact on total lifecycle costs up to 25%, WASP aims to reduce these expenses [241]. Remote autonomous inspection methods, particularly Autonomous Surface Vessels (ASVs) like the Global C-Workers (C-Worker 7, Figure 4-5B), offer close-proximity operations suitable for offshore turbine service. These ASVs demonstrate extended

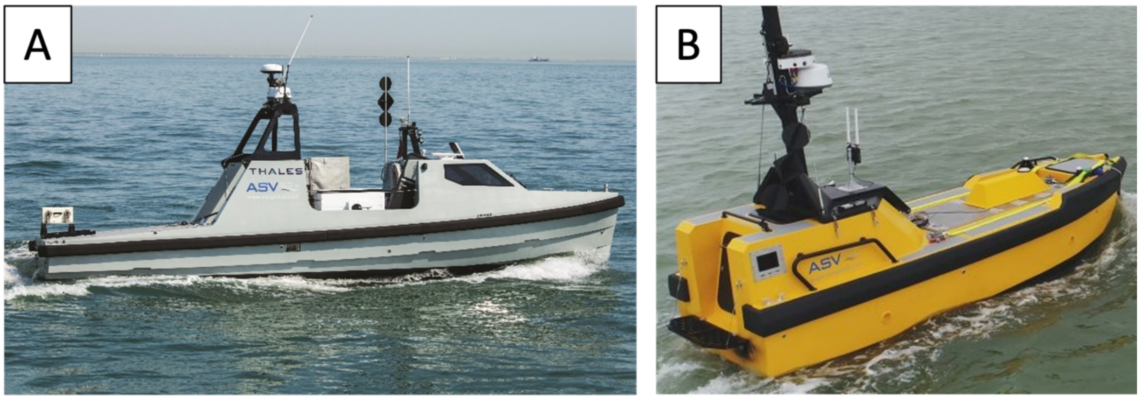


Figure 4-5 A. Thales Halcyon [238]. B Global C-Worker 7 ASV [241].

operational endurance of up to 25 days without refueling, leading to reduced costs and fuel consumption compared to conventional vessels [242]. The potential future use of unmanned service vessels could revolutionise logistical, surveying, and monitoring support, including aerial drone deployment. The feasibility study within the WASP activities identified challenges for ASVs operating in wind farm arrays, enabling the characterisation of ASV performance and the development of a route map for integrating ASVs into manned vessel operations within the sector [243,244].

Table 4-1 showcases companies that created their own robotic platforms, with a focus on widely accepted AUVs and UAVs. Figure 4-6 exhibits images of these robot types and their associated challenges alongside examples of companies which use them [245–249].

Demonstrated levels of increased robustness, agility and maneuverability have been achieved within companies seeing quadruped robots such as Anybotics Anymal, Boston Dynamics SPOT (Figure 4-6 E, F) and Unitree GO1/B2 releasing their own legged platforms across 2020/21 [250,251]. These attributes were previously considered challenges, however, further work has improved the baseline autonomy that these robots have achieved such as described in robot parkour and deep reinforcement learning for quadruped robots [252–254]. Perception and levels of autonomy will expect to result in full deployment in industrial assets going beyond case study experimentation and will lead to increased safety during continuous deployment for the operators of different facilities within sectors such as the energy sector.

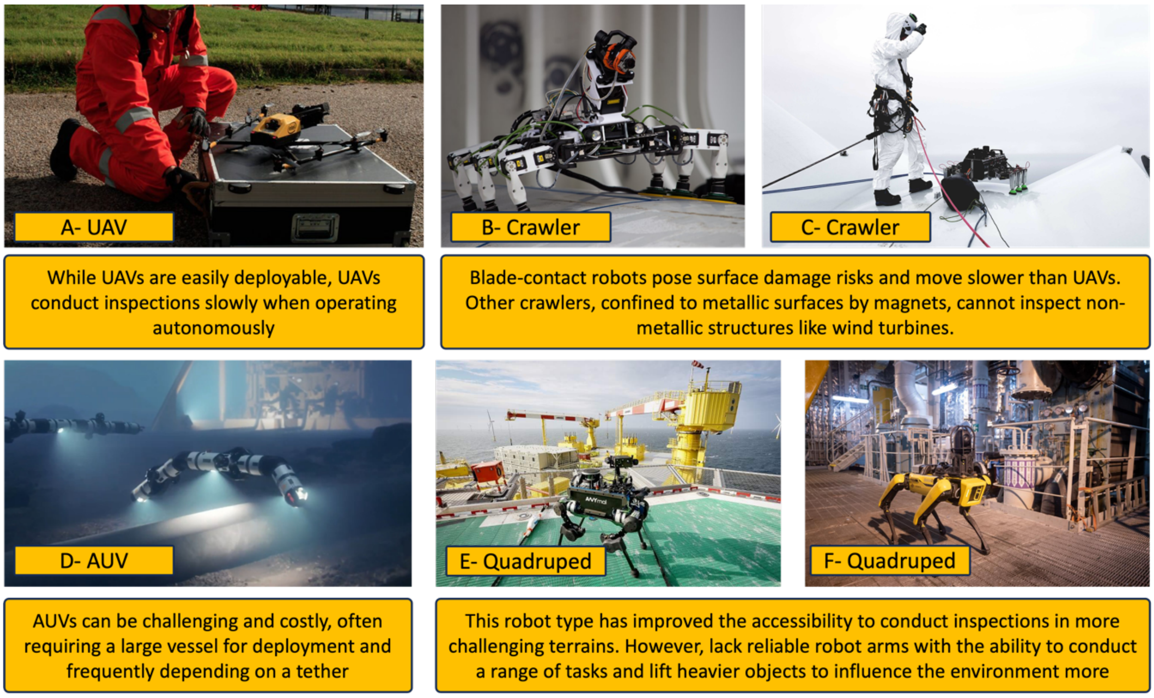
As previously described in section 3.1, digital twins result in digital replications of living and non-living entities enabling for data to be seamlessly transmitted between cyber and physical assets [10,255]†. With respect to the environments which the inspection robots

Table 4-1 A compilation of companies and their robotic platforms categorised based on their functionality and deployment level [245–249].

<table>
<tr><th>Robot Type</th><th>Figure 4-6</th><th>Function</th><th>Company Name</th><th>Mission Type</th><th>Autonomy Level (Refer to Figure 4-1)</th></tr>
<tr><td rowspan="2">UAV</td><td>A</td><td>Inspection</td><td>Cyberhawk</td><td>B/VLOS</td><td>3- Conditional Autonomy</td></tr>
<tr><td colspan="5">Performed 40,000+ flights for 300+ clients with certified drone pilots and an experienced inspection engineer, using the Intel Falcon 8. Weather-dependent inspections cover up to 6 turbines, detecting defects with a precision of ±5mm. Post-processing of defects is done with the iHawk viewer. Estimated savings of 36.8% compared to annual rope-access inspections. Secured a multi-million, five-year contract with Shell PLC for drone-based inspection services [476,477]</td></tr>
<tr><td rowspan="2">Crawler</td><td>B,C</td><td>Inspection & Maintenance</td><td>Bladebug</td><td>VLOS</td><td>2- Partial Automation</td></tr>
<tr><td colspan="5">The innovative electronic skin, Wootzkin, enhances the accuracy of a robot's vacuum system in attaching to blades through machine learning algorithms. It cuts blade maintenance tasks by 30%, decreasing reliance on rope-access technicians. Recently employed to navigate a 50m path on a 7MW Levemount wind turbine blade [245,247,478]</td></tr>
<tr><td rowspan="2">AUV</td><td>D</td><td>Inspection, Maintenance & Repair</td><td>Eelume</td><td>BVLOS</td><td>4- High Automation</td></tr>
<tr><td colspan="5">Self-propelled AUV with subsea docking, enabling confined space access and resident system housing. Reduces shoreline logistics, maneuvering accurately with a snake-like design. Modular payloads like gripper tools and sonar facilitate inspections with a U-shaped camera view [248,479]</td></tr>
<tr><td rowspan="2">Quadruped</td><td>E</td><td>Inspection</td><td>Anybotics</td><td>BVLOS</td><td>4- High Automation</td></tr>
<tr><td colspan="5">Autonomous inspection deployment on a converter platform in the North Sea wind farms in a partnership with Tennet (2018). The mission transmit run-time data collected by visual thermal, microphones and gas detection sensors [480,481]</td></tr>
<tr><td rowspan="2">Quadruped</td><td>F</td><td>Inspection</td><td>Boston Dynamics</td><td>BVLOS</td><td>4- High Automation</td></tr>
<tr><td colspan="5">SPOT, deployed by British Petroleum 305km offshore in the Gulf of Mexico on an O&G rig. Successfully navigated mesh flooring and stairs. Used for anomaly scanning, corrosion tracking, gauge checks, facility mapping, and real-time methane leak detection via onboard sensors for plant monitoring [15,246]</td></tr>
<tr><td rowspan="2">Digital Twin</td><td>N/A</td><td>Operation & Condition Monitoring</td><td>Osberg H</td><td>BVLOS</td><td>4- High Automation</td></tr>
<tr><td colspan="5">World's first fully operated O&G platform by Equinor, installed in October 2018. Anticipated yield: 110 million barrels through 11 wells with only two annual maintenance visits. Construction finished early at $750 million, 20% under the estimated cost. Fully automatic and remotely operated, it employs digitalisation, interconnected systems, and a digital twin for platform operation [482]</td></tr>
</table>

are being deployed in as in Table 4-1, the position that a digital twin fits becomes important as it enables for a human operator to trust that an asset is deployed and acting as intended. For example, wind farm arrays are being positioned further offshore to capture stronger winds, therefore, the robots tasked with inspecting these assets will also be deployed further offshore and perhaps resident to the asset. A digital twin will enable for trusted BVLOS operations to take place. However, there is a possibility that different variables or warnings can be under-represented, such as high winds and a storm where the severity of such a event may be under-represented. In addition, it should be noted that the opposite can occur where a mission may not take place as a light storm could be over-represented. This can also be applied to failures within infrastructure where they could be under-represented too, for example, a malfunction within a switchboard whch could lead to a blackout in a certain area of a plant. Finally a human operator may also potentially trust erroneous data within a DT rather than investigating onsite leading to further damage or inefficiencies.

Additional challenges and obstacles for robotic platforms involve inspection robots operating in close proximity to high voltage sources, necessitating solutions for electromagnetic interference and potential arcing. In environments with electromagnetic harshness, accurate localisation in GPS-denied and dark conditions, along with effective fault detection, is crucial to support existing condition monitoring systems [256,257]. Despite advancements in technology, there is a notable gap in regularly deploying robotics



While UAVs are easily deployable, UAVs conduct inspections slowly when operating autonomously

Blade-contact robots pose surface damage risks and move slower than UAVs. Other crawlers, confined to metallic surfaces by magnets, cannot inspect non-metallic structures like wind turbines.

AUVs can be challenging and costly, often requiring a large vessel for deployment and frequently depending on a tether

This robot type has improved the accessibility to conduct inspections in more challenging terrains. However, lack reliable robot arms with the ability to conduct a range of tasks and lift heavier objects to influence the environment more

Figure 4-6 A summary of general robotic platforms including benefits and challenges [245–249].

and artificial intelligence offshore. The absence of uniform and adaptive regulations, lack of standardised infrastructure and equipment design, and insufficiently trained workforce hinder seamless deployment. Industrial concerns regarding equipment malfunctions and cyber-attacks persist, highlighting the need for a mindset shift in trusting autonomy and robotics and artificial intelligence reliability within the workforce. The design of robotics plays a pivotal role, requiring autonomous systems tailored to specific missions and environments.

4.1.3. Hype Cycle Overview of Mobile Inspection Robots

Hype cycles allow for assessing market promotion and perceived value of innovations, comparing consumer reality with hype. Initial expectations of robotic platform performance are often high but may not align with actual capabilities. The hype curve reflects technology potential versus reality, shown in Figure 4-7 over time. Key segments include:

Innovation Trigger: Railed robots see increased applications, especially in the offshore wind industry, although their integration in early design stages is challenging.

- To provide context, railed robots are typically used to move robotic manipulator arms around a facility [258]. With respect to this article, this would be unachievable due to the restricted area within a nacelle. Therefore, we address opportunities for compact railed robots which are the size of a small handheld drone and can follow a rail to complete repeated inspections however, other applications do not yet require more compact devices [259,260]. Rail-guided robots face competition mainly from lightweight, compact UAVs which can fly within confined spaces. However, a rail guided robot can carry heavier payloads and operate consistently to reduce risk of collision with infrastructure. However, many rail-guided robots require retrofitting the area which they are to be deployed in or included from the design phase of infrastructure [261].

Peak of Inflated Expectations: Climbing robots ascend structures but may lack speed, versatility, and accuracy compared to rope-access engineers. Payload limitations are also common.

- Climbing robots have steadily risen in adoption however may not be fully integrate able within the ORE sector as wind turbine operators prefer for a non-contact approach to inspection and maintenance. Rope-access crews and UAVs are still preferred as engineers worry that a climbing robot can cause defects on the blade that it is perhaps inspecting, whereas, with a rope access inspection, there is less risk in defect. However, to date, suction cup adhesion [262], vacuum cup adhesion [263,264], magnetic adhesion [265,266] and rope gripping are the main techniques for climbing alongside some bioinspired approaches which, whilst novel for their application, are not worth discussing with respect to IMR as majority are unable to carry payloads required. Additional notable overviews of climbing robots can be found here [267,268].

Trough of Disillusionment: ASVs and AGVs reach limits in current capabilities. ASVs play a role in logistics but face restrictions until autonomy improves. AGVs benefit from cheaper payloads but often require teleoperation.

- AUVs encounter distinctive challenges arising from the demanding underwater environments in which they operate. One major hurdle involves enhancing communication methods for underwater vehicles to enable robust and near-real-time operation. While improvements can be made by enabling a robot to operate resiliently using its onboard systems and reporting back to base when in its docking station - reducing the need for high-bandwidth wireless communications - it also introduces challenges related to autonomy and localisation, particularly in murky waters if issues arise [269–271].
- ASVs are increasingly being used for marine exploration within industrial activities such as environmental monitoring and surveying the seabed [272]. A vessel being partially in the water and above sea-level provides significant communications advantages when compared to subsurface vessels as it can communicate easily through the air and utilise sensors to inspect below the water. Many autonomous surface vessels utilise GPS to conduct their missions making them very reliable when out at sea [273]. For inspection the vessels can use a range of sensors to inspect foundations of wind turbines and the seabed [273–275].
- Whilst AGVs are not necessarily a key requirement for the offshore wind sector, there are opportunities which arise within offshore substations and other sectors such as the Nuclear and oil & gas sectors. Key considerations include sensor type, battery duration, environmental protection (such as radiation protection or from weather) and size to ensure the IMR task is conducted appropriately [132]. AGVs sit within the trough of disillusionment as they will play key roles as part of MR-fleets due to

the extended battery life and will greatly compliment other robots in long distance operations or carrying heavier equipment or sensors.

Slope of Enlightenment: Quadruped robots advance due to overcoming robustness barriers, addressing balance issues, and handling various terrains.

- Quadrupeds have reached the slope of enlightenment as they have now overcome their main challenge in terms of mobility to access basic areas such as flat solid ground, unstructured terrain and stairways, however, there are still improvements in achieving consistent navigation in confined spaces and with manipulation activities to ensure easier access to areas. Similar applies to wheeled robotic platforms, whilst these have improved battery durations, there are still improvements yet to be made on the software level where improved autonomy can enable for increased number of activities to be undertaken by the robots.

Plateau of Productivity: UAVs are readily deployable but still rely heavily on remote human control and lack full autonomy. Advances are needed in autonomous capabilities.

- As a result of improved control, accessibility and payloads, UAVs have currently reached a significant stage where there is value in regular deployment. However, with respect to autonomy, they are at a developmental barrier as they are currently unable to achieve true BVLOS operation. Current factors include improved decision making, improved energy density to carry heavier payloads alongside significant improvements in flight durations. Finally, there are many inefficient payloads for UAVs which are limited to surface measurements such as thermal or visual imagery. Some sensors do have the ability to detect subsurface features however do require contact with the surface which should be avoided in the wind sector [36,276–278]†§.

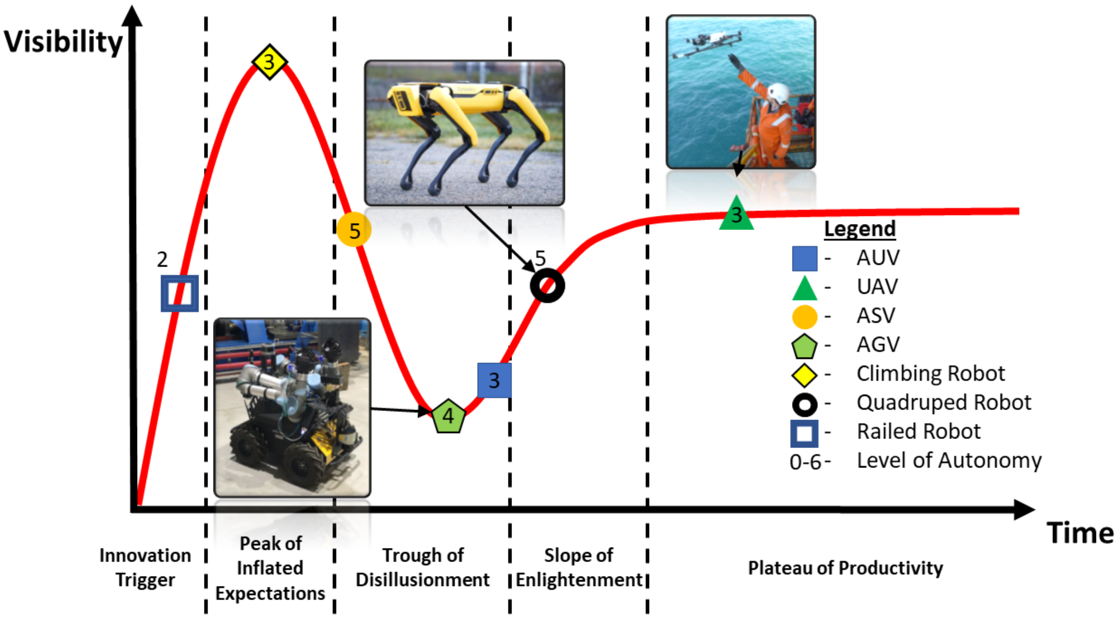


Figure 4-7 A hype curve displaying method of deployment of robots relative to their hype curve highlighting their visibility and autonomy with respect to time of innovation [20,278]†.

4.2. DARPA Subterranean Challenge

The Subterranean (SubT) challenge was created by the Defence Advanced Research Projects Agency (DARPA) where the objective was to create ground-breaking technologies that enhance subterranean operations. The research devised novel methods to expedite mapping, navigation, search and rescue efforts, and the exploration of intricate underground environments, including artificial tunnels, urban subterrains, and natural cave networks (see Figure 4-8A). These challenging contexts pose difficulties for both military and civilian first responders, as hazards can significantly differ across terrains that may evolve over time, rendering it too dangerous for personnel to enter. The aim of deploying the robots is to establish run-time situational awareness from a small team of humans whose MR-fleet must enter an undetermined dynamic underground (communications denied) environment. Some challenges the robots face include collapsed mines, post-earthquake and search and rescue in these areas. Alongside challenges of overcoming an unstructured environment, the teams gain points for successfully identifying (and localising the items within a set threshold of within 5 metres) different artefacts throughout the environment including a survivor manikin, backpack, mobile phone, helmet and other potential signs of a survivor. The work demonstrated elements of both top-down approaches to MR-fleet coordination however, mostly focused on ground-up capabilities including detection of artefacts, and navigation and mapping. A reminder of top-down versus ground-up approaches can be viewed in Figure 3-3 [9]†.

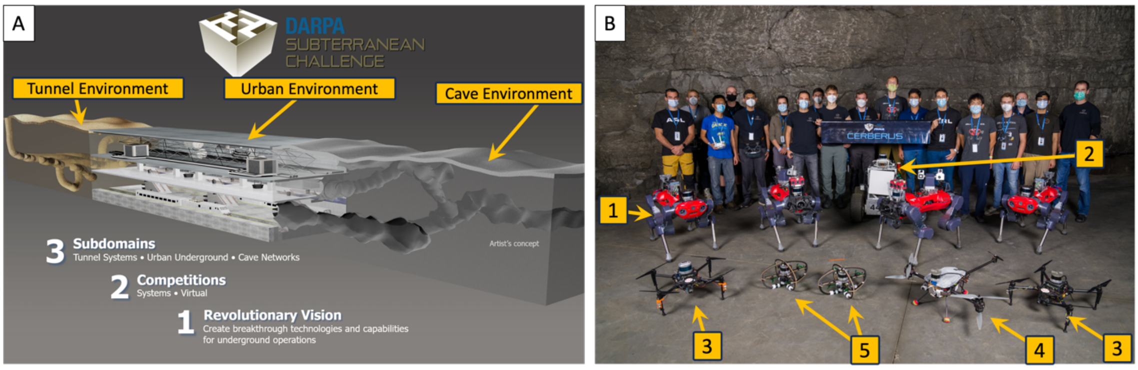


Figure 4-8 A- Overview of the three key areas within the DARPA SubT challenge. B- Team CERBERUS alongside their MR fleet. 1- 4x Anybotics Anymals 2- Armadillo roving robot, modified Inspectorbots Super mega Bot, 3- 2x DJI Matrice 100, 4- Kolibri Flying Robot , 5- 2x Gagarin RMF-Owl UAVs [280,281].

In this section, a thorough literature review is provided, drawing from the Special Issue on Advancements and Lessons Learned in DARPA SubT Challenge Phase I and II. The content focuses on identifying common areas of enhancement and challenges discussed in the articles concerning MR-fleets. Table 4-2 includes a compilation of keywords and their corresponding definitions.

Team CERBERUS (CollaborativE walking & flying RoBots for autonomous ExploRation in Underground Settings) secured the top position in the competition and are pictured in Figure 4-8B [279–281], followed by CSIRO (Commonwealth Scientific and Industrial Research Organisation) in second place [282] and MARBLE (Multi-agent Autonomy with Radar-Based Localisation for Exploration) claiming the third spot [283]. A video showcasing the winning round for Team Cerberus can be viewed within Tranzatto *et. al* [284,285] where some key images related to deployment type and environment is displayed within Figure 4-9. The key challenges identified are discussed in these articles pertaining to the event [286,287]. In this literature review's analysis, we concentrate on challenges inherent in MR-fleet approaches, with a particular emphasis on operator overload, communication issues, and robot failures, as outlined in Table 4-3. Firstly, we summarise the requirement for each column within the outlined table. We realise that operator overload is something that is difficult to evaluate within this article considering we were unable to monitor the state of the HITL however, we have carefully analysed the articles presented at the event and identify several instances related to this challenge. Identifying operator overload is challenging due to the absence of a quantifiable or qualifiable method. However, we characterise cognitive overload as the perceived mental effort influenced by factors such as task design, task

Table 4-2 Keywords and Definitions [9]†.

Keyword	Definition
Resilience [171]	The ability to recover from unforeseen circumstances such as environmental variables, unstructured environments where the robot can overcome adversity to maximise the current task success rate
Reliability [173]	Reducing risk onboard a robot and maximising state of health via monitoring and ensuring the operational ability of the onboard systems maximising the mean time to failure
Operator Overload [292,483]	Psychological stress and anxiety resulting in the human making mistakes, only focussing on urgent tasks, forgetting about the use of other robots in the fleet and forgetting the wider strategy of the challenge
Communications [402]	Exchange of information across robots and to the HITL via different methods of communication including wired and wireless
Robotic Failure [484]	The circumstances during design, manufacture or use that lead to a failure mode during operation
Robotic Teamwork [485]	Working collaboratively as a team to achieve improved inspection capability or overcome adversity in dynamic environments
Virtual Interactions	Improving the situational awareness in a robotic fleet when two or more robots share data leading to improved information about a mission. E.g. Map sharing
Physical Interactions	On-site interactions between two robots. -A robot utilises a second robot to improve the visibility of an area. (Room filled with smoke, robot A has visual camera and robot B uses its thermal camera to guide robot A to safety) - Robot A requests the manipulator from robot B to free a cable restricting robot A's operation
Symbiotic Interactions	Taking the form of either virtual or physical within a robotic team where several robots collaborate directly to overcome mission challenges relating to inspection, wireless communication or robotic failures. This reduces the requirement for humans to intervene and replaces it with robotic intervention via symbiotic interactions

quantity, and task urgency [288]. In the DARPA Sub-T, a solitary human operator is mandated for mission control [289]. Operator overload could hinder inspections if the user receives excessive, insufficient, or untimely information, causing stress and detrimentally impacting the mission [290]. Wireless communications reflect the deployment effectiveness, assessing potential breaks in the communication chain that hindered the MR fleet. Robotic failure was examined in terms of the robot's suboptimal performance during task completion. This encompassed failures during navigation over stairs, in diverse environments, or damage sustained by robots, as well as the evaluation of implemented recovery methods [9]†.

Secondly, the following publications are analysed in Table 4-3 for the three factors. Since the teams are limited to a single human operator overseeing and interacting with the mission from the dashboard interface this often resulted in operator overload in the instance that mission resilience challenges were faced during artefact detection [291]. In some instances, the robots were also teleoperated resulting in potentially 3 key roles for the single human operator, namely teleoperation of a robot, overseeing operation of an autonomous robot and decision making in verifying suitable instances of artefact detection [279,282,283,292]. Therefore, a high level of concentration was required across long durations by the HITL operator [283]. To provide context relative to concentration and the demand for multi-tasking, some teams were detecting artefacts around 13 times a minute, overwhelming the operator. Especially in the example where the human operator is required to teleoperate a robot (for instance, navigating through debris or within confined passageways.) and when the robots incur damage [282,293]. However, different approaches included that of Team Nebula who tried to offload some decisions to an automated co-pilot to overcome this issue [9,294]†.

Several teams prioritised addressing communication challenges arising from data sharing within tunnels, where wireless communications were restricted. Some teams employed mesh networks, facing reliability issues when deploying wireless nodes in the tunnels.

Figure 4-9 Deployment types and varying environment presented in the DARPA SubT event. A- Viewpoint from tunnel entrance, B- Tracked robot in urban environment, C- quadruped in urban environment, D- Quadruped in cave circuit, E- Quadruped deploying wireless node in cave circuit and F- UAV in urban environment [289].

Additionally, autonomous traversal by certain robots caused damage to the mesh networks. In specific stages, a couple of teams relied on their robots traveling to the tunnel access area (near the mission start point next to the base station) to establish wireless connectivity for data exchange. Finally, another team utilised an optical cable to overcome delays in teleoperation and to communicate with the wireless portion of the team [9]†.

Finally, concerns regarding robotic failures within the mission profiles were identified. These failures pertained to instances where robots encountered issues that left them stranded or incapable of proceeding positively within the mission profile. Primarily, these failures stemmed from navigation autonomy being unable to overcome obstacles in unstructured terrain. For instance, a quadruped robot slipped while navigating over a railway track, rendering it unrecoverable due to a system failure [282]. A tracked robot experienced a shutdown on a stairway when its tracks slipped, resulting in a collision that required the HITL to shut down the robot. Additionally, the same team encountered a post-mission catastrophic failure caused by condensation build-up during the event, resulting in issues with their Clearpath Husky robot after the event (which has an operating temperature of between -10 and 40°C and an IP rating of either IP 44 or IP 55 depending on which model was purchased from Clearpath Robotics) [9,221,295]†.

In anticipation of potential robotic failures in the lead-up to the DARPA SubT challenge, many teams proactively devised various strategies. For instance, Rouček et al. [295], implemented software that accommodated failures and aimed to mitigate them upon occurrence. Agha et al., along with Team CoSTAR [294], developed recovery mechanisms that generally proved effective; however, their future plan involves enabling the system to predict failure and adapt to it when it occurs. Other teams also addressed HITL considerations, involving the need to identify failures and teleoperate the robot to overcome various challenges as they arose [9]†.

Robotic teamwork was also analysed as all of the teams deployed a wide range of robotic platforms which could allow for a wide range of capabilities to be captured and overcome in relation to reliability, resilience and mission optimisations. As previously discussed, several robots faced robotic failures such as team CERBERUS who had a tangled optical cable on their tethered robot. This tether was vital for continued exploration further into the cave and for ensuring optimal communications between HITL and and robots in the nearby area [279]. Had the team devised a contingency plan involving robotic teamwork, the failure could have been resolved by deploying a robot equipped with a manipulator arm to untangle the optical cable. This collaborative effort would have restored the tethered robot, enabling further exploration into the mine shaft. Notably, an unintentional instance of robotic teamwork to overcome failure did occur in one of the teams when a husky robot was freed to overcome navigational challenges by a tracked robot. The tracked robot was deliberately rammed into the Husky to dislodge it, however, this resulted in a parasitic interaction as the Husky was now operational, however, the tracked robot now displayed a failure due to inaccurate mapping resulting from the jolt in the crash [295].

Table 4-3 The results and findings of the teams competing in the DARPA SubT event [9]†.

[†]Indicates analysis or conclusions made by the authors in their article of their own work.
[*]Indicates analysis or conclusions made by the authors in our critical analysis.

Publication and ***Fleet Specification***	**Operator Overload**	**Communications**	**Robot Failure**	**Robotic Teamwork**
CERBERUS: Autonomous Legged and Aerial Robotic Exploration in the Tunnel and Urban Circuits of the DARPA Subterranean Challenge [279] 1st Place *3x Anymal B quadrupeds* *3x DJI Matrice 100 UAV* *1x Modified wheeled Super Mega Bot*	1)Lack of a single unified UI[†] 2) Complex UI (Difficult to comprehend by user in high pressure[*]) for gathering information from robots (maps, camera streams, artefact detection) [†] 3)Lack of ability to relocate the robot when robot virtual position doesn't match real position[†]	1)Reliability issues in functionality of breadcrumb WIFI nodes[†] 2)Wrong decisions where to position breadcrumb nodes and tilted nodes resulted in weak connections[†]	1)Tangled tether during mission[†] 2)ANYmal quadruped stuck on obstacle in new environment with no connected comms therefore unrecoverable[†]	1)Robots dropping WIFI nodes[†] 2)Map/data Sharing[†] 3)No physical interactions across MR-fleet[*]
Heterogeneous Ground and Air Platforms, Homogeneous Sensing: Team CSIRO Data61's Approach to the DARPA Subterranean Challenge [282] 2nd Place *1x CSIRO hexapod (Legged robot)* *1xGhost robotics quadruped* *1xEmesent UAV*	1)Autonomous navigation was more reliable in challenging environments than teleoperation[†] 2) Artefact detection rate overwhelmed the operator[†] 3)Operator required to assist stuck robot and reprioritisation of tasks[†]	1)Shut down wireless communications project to use off-the-shelf product (Rajant Mesh System) [†] 2)Operator spending large amounts of time troubleshooting communications[†] 3)Robots damaging comms network by driving over WIFI nodes[†]	1)Ghost quadruped slipped on rail and was unrecoverable at 40m from start of mission[†] 2)Tracked robot beached in single mission[†] 3)Minimal damage sustained on robots where some robots continued after a roll affecting robot orientation and collision[†]	1)UGVs carrying UAVs[†] 2) Shared map data enabled for coordination of exploring regions away from other robotic agents[†] 3) Improvements will address platform robustness and stability[†] via platform design[*] 4)No physical interactions across MR-fleet[*] 5) Future work includes focussing

1xBIA5 ATR tracked robot *1xSuperdroid LT2-F tracked robot* *1xCSIRO DTR tracked robot*			4) Stuck robots required remote human intervention due to insufficient modelling of risks in challenging terrain†	on coordination, platform heterogeneity and autonomy†
Multi-Agent Autonomy: Advancements and Challenges in Subterranean Exploration [283] 3rd Place *1x Clearpath wheeled Husky* *1x Lumenier QAV500 UAV* *1x Superdroid HD2 tracked robot*	1)Manual control was least desirable but often warranted in many cases† 2) Errors in position data acquired for artefacts required manual data entry by HITL† 3) A requirement to assume manual control in unforeseen circumstances or to investigate areas of interest resulting in additional load on a HITL managing multiple robots†	Increased success rate of artefact image transmission from 30-100% via map diffs resulting in low-bandwidth data and point-to-point messages for map diffs and artefact images† Challenge of designing a multi-agent systems which can handle robots leaving comms regularly with respect to coordination of the robots† Overcome network saturation and reliability issues throughout UDP-Mesh communications†	Mostly performance issues than failures† 1)7 false IDs during artefact scanning with 8 reported in wrong position in 24 scans (required HITL intervention) † 2) Limited number of platforms resulted in less area covered when compared to other teams†	1)Multi-agent communication hopping- tactic used to share information to HITL through other robotic platforms which worked effectively even without coordination† 2)No physical interactions across MR-fleet asides from sharing of messages*
A Heterogeneous Unmanned Ground Vehicle and Blimp Robot Team for Search and Rescue using Data-driven Autonomy and Communication-aware Navigation [291] *1x Blimp UAV* *1xClearpath wheeled Jackal* *2x Clearpath wheeled Husky* *1x Spherical robot* *1x Race car robot wheeled*	1)Operator overload not mentioned but considered likely due to high task volume for HITL* 2)All decisions made by human, human selects location for drop nodes, assigns subgoals for unexplored regions*	1)Relied on moving WIFI access points in addition to static anchor nodes† 2)Attempts to establish communication metric across equipment. Quantitive measurements for when/where to drop WIFI nodes†	1)Unmanned Ground Vehicle (UGV) stuck on ledge (unrecoverable) † 2)Unstructured terrain lead to SLAM failure increasing mean odometry and mapping error, resulting in inaccurate artefact detection (>5m). †	1)Spherical and race car robots as mobile WIFI nodes† 2) Collaborative mapping only† 3)No physical interactions across MR-fleet*
Resilient and Modular Subterranean Exploration with	1)Majority of stuck robots abandoned due to operator overload enabling	1)Lag in wireless comms when recovering robots via teleoperation†	1)Robot stuck on stairway†	1)Attempts made to free robots using other robots but

a Team of Roving and Flying Robots [292] *3x custom ground robots* *2x custom UAVs*	operator to focus on coordination of other robots and detection of artefacts† 2)Unable to recover robots via joystick†	(No quantifiable indication other than negatively affected HITL teleoperation*) 2)Build comms network with one robot to maximise exploration (via communication beacons*). This method was soon abandoned due to speed issues† 3)Robot stuck outside of wireless comms became abandoned†	2)Robot motor failure and abandoned † 3)Robot stuck with human operator unable to recover it† 4)Navigation maps became misaligned and required mission restart†	manually teleoperated† 2)UAV launched from UGV but landed at the entrance of the course after their mission†
NeBula: TEAM CoSTAR's Robotic Autonomy Solution that Won Phase II of DARPA Subterranean Challenge [294] *2x Boston Dynamics Spot quadruped* *6x Hybrid vehicles* *4x Clearpath wheeled Husky* *1x Tracked Telemax* *1x Small rover* *2x Small custom UAV*	1)Operation module to aid human supervisor interaction with the UI† 2)Auto co-pilot handles several decision-making processes (tasks) to minimise overwhelming HITL however, requires HITL to trust it† 3)HITL ready to assist with mission critical tasks† 4) Human viewed as a resource and intervention task management †	1)Quality of Service Data Distribution Service via Collaborative High Bandwidth Operations with Radio Dropables (CHORD). Mobile and static communication nodes† 2)Minor change in USB driver and network bandwidth limitations resulted in unexpected failure†	1)UAV critical failure due to poor lighting at 35 m from start† 2)Dust was a major issue causing vision-based state estimation failures for UAVs† 3)Recovery behaviours mostly worked and provided no catastrophic failure† 4)Critical failures/km for each robot†: skid steer-0.2 Tracked-0 Ackermann-0 Quadruped-1.1 5)A key lesson in future was to allow system predict failure and adapt to failure when it occurs†	1)Communications sharing data only† 2)Human-machine teamwork in terms of autonomous co-pilot to reduce operator load when doing main tasks* 3)No physical interactions across MR-fleet*
System for multi-robotic exploration of underground environments CTU-CRAS-NORLAB in the DARPA	1) Flipper control (for traction) on tracked robot completed autonomously to reduce cognitive load and due to time lag in communications†	1)UDP protocol means connection state is not affected by wireless link state- transmits when link is available†	1)Software allows for failures and tries to mitigate them† (resilience*) 2)Tracked robot shutdown on stairs, flippers	1)Communications sharing data† 2)Husky was freed by tracked robot bumping into it to tip over and break free although Husky rescue

Subterranean Challenge [295] *1x Clearpath wheeled Husky* *1x Bluebotics SA Absolem tracked robot* *1x Hexapod crawling robot* *1x Aerial quadrotor robot*	2)Most runs were either teleoperated or heavily influenced by human operator via waypoint navigation directions†	2)No wireless link for UAV initially then would transfer data if close to course entrance† 3)Teleoperation of robots with 10 seconds delay†	lost traction and caused crash. Robot unable to overturn due to unrecognised behaviour, HITL shutdown robot† 3)8°C and 100% humidity. Husky broke down after event due to condensation on internal components†	caused tracked robot to lose mapping and be lost†. A minor example of teamwork to overcome a problem*
Teleoperation for Urban Search and Rescue Applications [293] *2x Large Ackermann wheeled robots (repurposed SMP Robotics S series)* *2xSmall custom skid steer wheeled robots* *8x custom UAVs*	1)Teleoperation approach limited multiple agents advancing through circuit at the same time† 2) Cognitive load on operator expands as the area to search increased†	1)Wireless daisy chain configuration to maintain communications† 2)Robot with fibre optic cable for communications†	1)Failure of dispensing mechanism for repeater node overturning robot† 2)SLAM began to become unstable†	No direct robotic teamwork present, however, used a diverse multi robot fleet to tackle challenges in terrain*

In conclusion, this subsection pinpointed shared issues and challenges among many teams, including operator overload, communication issues, robotic failures, and the need for effective robotic teamwork. Consequently, a novel approach which has inspired this research from key learnings in the DARPA SubT challenge utilising symbiosis is suggested and is essential to enhance the current state-of-the-art in MR team missions as discussed within Section 5 onwards.

4.3. Cyber Physical Human Systems

This literature review has identified a trend where individual robots are being deployed in more scenarios as a robotic fleet to accomplish more and capture more information about an environment. This is being achieved via a diverse deployment of robotic platforms (E.g. legged, wheeled and aerial) and a wide range of payloads onboard robots (E.g. LiDAR, cameras and thermal cameras). The examination of real-world issues is a fundamental component of technology development where competitions such as DARPA SubT allow for challenges to be set and addressed. Industry sectors such as the ORE and nuclear sector have many shared challenges with the DARPA SubT to overcome issues in IMR activities.

However, this thesis has also identified a key trend where diverse robots operate alongside each other connected to a digital interface with a HITL operator. To date, this concept has been primarily presented as a cyber physical system however, is shifting to a Cyber Physical Human System as the robots become more coordinated as a team and the human gains more interaction and influence amongst the fleet/mission profile. In this section of the thesis, a Scopus database bibliometric search is first employed to identify essential components of research pertaining to cyber physical systems and key sectors associated with industrial asset management. Secondly, the applications of cyber physical human systems are presented with respect to the key sectors identified via Scopus.

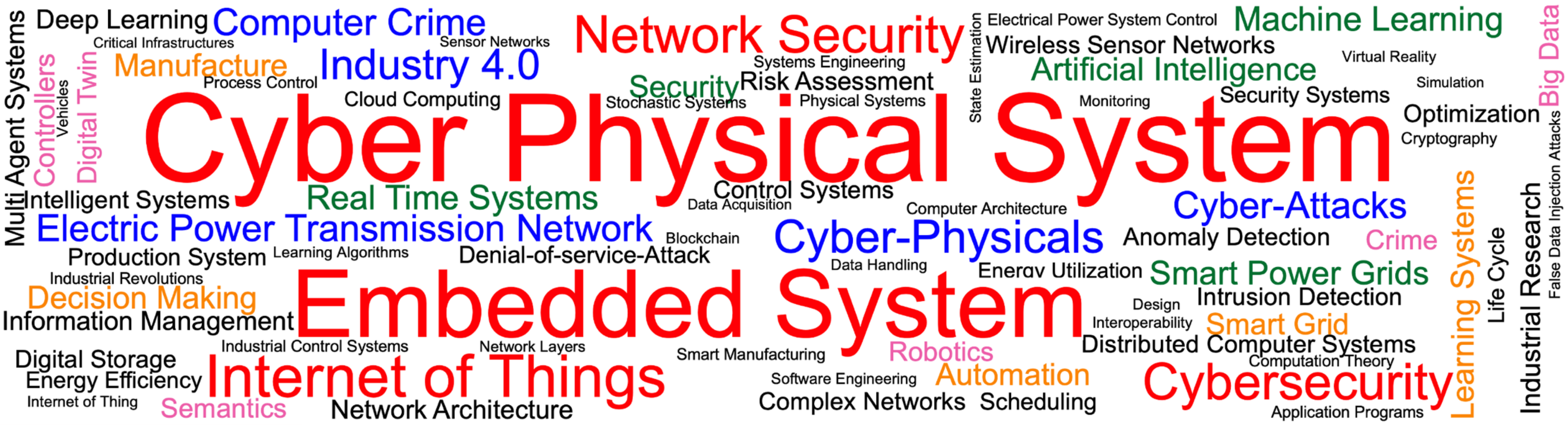
4.3.1. Bibliometric Search

To establish a comprehensive understanding of the research landscape, bibliometric analysis of the primary term ‘cyber physical system’ was conducted to identify the keywords, topics and offer a visual representation of the frequency of terms within published research. This enables the identification of key concepts, exploration of relationships, discovery of new keywords and a visual communication tool. The following terms were grouped to ensure a comprehensive search methodology:

1. ‘cyber-physical system’, ‘cyber physical system’ and ‘cybe-physical system’.
2. ‘cybersecurity’ and ‘cyber security’.
3. ‘robotics’ and ‘robot’.

The analysis from the bibliometric search identified 34,754 articles created with the term cyber physical system where 32,710 were published since 2010. The word-cloud within Figure 4-10 displays the top 25 words colour-coded relative to frequency. The aim of this search was to identify the key research areas related to cyber physical systems and presents terms ‘embedded systems’, ‘IoT’, ‘network security’ and ‘cybersecurity’. Furthermore, terms associated with sectors encompassed 'electric power transmission networks' (ranked 10th), 'smart power grids' (ranked 12th), 'automation' (ranked 16th), 'manufacturing' (ranked 18th), and 'computer crime' (ranked 9th), in addition to the broader term 'crime' (ranked 21st). Less frequently used words are denoted in black.

To ensure comprehensiveness in the trend analysis, a keyword search was performed on the 34,754 articles searching for the key sectors such as ’Energy’, ’Healthcare’, ’Automotive’, ’Aerospace’, ’Nuclear’, ’Oil and Gas’ and ’Offshore.’ Figure 4-11 presents a trend where 2010 results in an increase in the number of publications related to cyber physical systems for the energy sector. This pattern continues beyond the graph, reaching its pinnacle in 2022 with 2,085 articles, as appropriately indicated. The remaining sectors experience an increasing trend around 5 years later by 2015. Similar trends are evident in data related to other sectors, where the healthcare and automotive sectors stand out with a higher number of publications, followed by modest increases in other sectors. This can be attributed to various sectors acknowledging the necessity and impact of cyber-physical systems. While this article concentrates on industrial asset management, it's noteworthy that the healthcare sector has adopted cyber-physical system approaches to enhance existing capabilities. This,



Red Text

Rank	Word	Freq
1	Cyber Physical System	35786
2	Embedded System	19782
3	Internet of Things	5424
4	Network Security	4047
5	Cybersecurity	3928

Blue Text

Rank	Word	Freq
6	Cyber-Physicals	3176
7	Industry 4.0	2561
8	Cyber-Attacks	2063
9	Computer Crime	2018
10	Electric Power Transmission Network	1980

Green Text

Rank	Word	Freq
11	Machine Learning	1713
12	Smart Power Grids	1596
13	Real Time Systems	1566
14	Security	1414
15	Artificial Intelligence	1331

Amber Text

Rank	Word	Freq
16	Automation	1323
17	Decision Making	1286
18	Manufacture	1278
19	Learning Systems	1278
20	Smart Grid	1214

Pink Text

Rank	Word	Freq
21	Crime	1188
22	Controllers	1061
23	Robotics	977
24	Semantics	944
25	Big Data	942

Figure 4-10 A word-cloud displaying the frequency rank table illustrating terms linked with CPS from the bibliometric analysis.

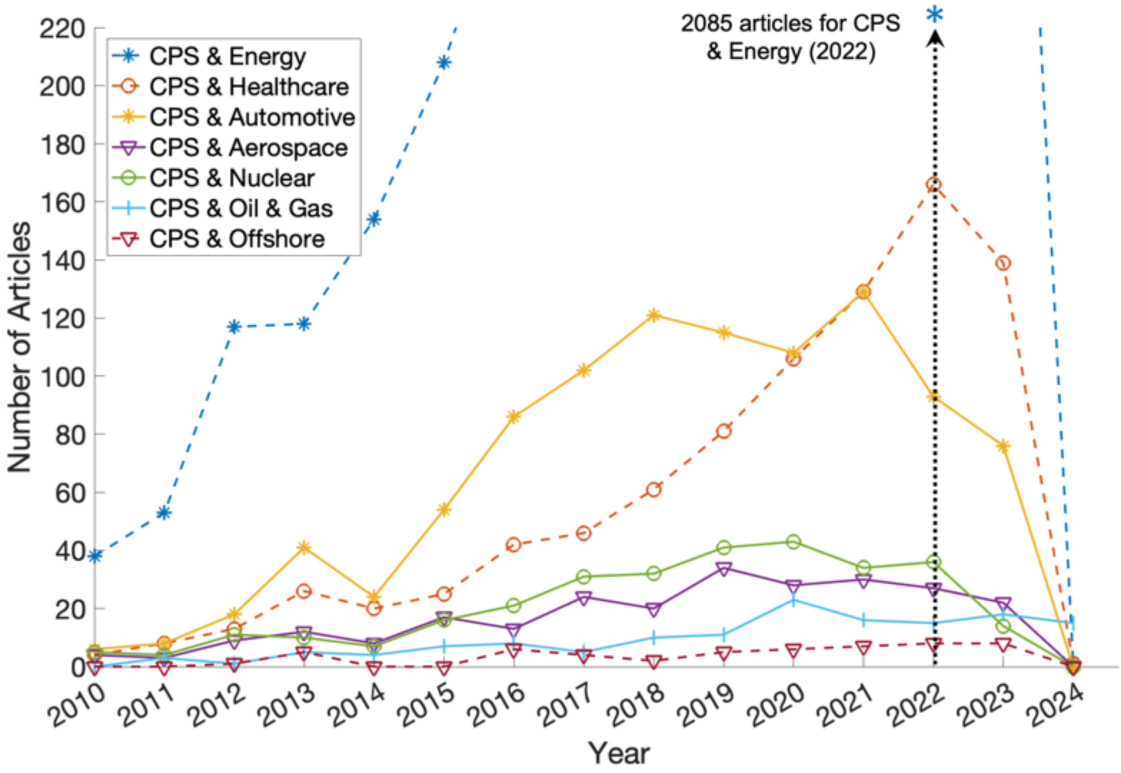


Figure 4-11 Examination of keywords presenting keyword searches combining CPS with different sectors.

in turn, has likely paved the way and encouraged the implementation of similar systems in sectors engaged in industrial asset management, which will be discussed subsequently [296].

4.3.2. Aerospace

The Apollo 13 mission is regarded as the first digital twin deployed in the aerospace sector which has allowed for the design and development of digital twins to date [297]. Subsequently, digital twins have emerged as significant contributors to the aerospace industry, particularly in training where virtual flight hours are essential for pilot training protocols. In the field of IMR within aerospace, there has been research exploring the utilisation of digital twin technologies for monitoring asset integrity in airframes, as well as the deployment of robotic arms for IMR and aircraft assembly [298,299]. Nevertheless, studies and technology applications related to IMR robots are currently constrained, predominantly concentrating on aspects including control, computational capabilities, and resilience to dust contamination.

4.3.3. Manufacturing and Automotive

The manufacturing and automotive sectors represent two leaders in the adoption of industry 4.0 technologies representing vital use cases of digital twins. Cyber physical twins to date have mainly been used in the production stage for components and vehicle assembly

[300,301]. The Siemens Amberg factory is a 1,200 square foot facility which manufactures 1200 different projects. Changing the production line to accommodate the 1200 different designs used to be a challenging problem. However, digitalisation of the products has enabled for streamlining of the manufacturing process leading to rapid streamlining for new configuration. The production line for a product is created in a digital world where bottlenecks, inefficiencies or unexpected circumstances can be discovered and changed to optimise the process. The impact from digitalisation increased production by 1400% and has been named a lights-out manufacturing due to automation processes between the cyber-physical systems which produce the products which require no personnel when running [302,303]. The benefits of incorporating digital twins in these industries are predominantly evident in optimising key processes rather than emphasising IMR. This motivation stems from the desire to minimise downtimes between stages and facilitate greater flexibility in scaling production based on demand.

4.3.4. Nuclear Energy Sector

To date, the UK is mainly focused on maintenance and decommissioning of its nuclear sector. This provides a key opportunity for lessons to be learned in the deployment of robotics and autonomous systems to improve the safety during the decommissioning phase. However, it should be noted that opportunities will still exist for how to use robots for IMR of the same facilities. The deployment of robotic systems and creation of cyber physical human systems will improve these processes and increase safety for personnel. Notable use cases include the following:

- The safe identification and disposal of nuclear material [304].
- Utilisation of several robotic sensors for remote inspection [305].
- Radiation [148,306].
- Remote handling for glovebox operations [307,308].
- Haptics [309].
- Detection and maintenance of anomalies within fusion reactor tiles [310].
- Snake-arm robots to inspect confined spaces [311].

Whilst these technologies and advances represent the state-of-the-art, a unified approach via a cyber physical human system enables for full integration of diverse sensors for industrial asset management. This includes areas such as cooperative inspection and anomaly detection for the nuclear sector which is yet to be established and critical in the future pathway.

4.3.5. Offshore Energy

As previously presented in Chapter 2 Market Trends Accelerating the Growth of Robotics, industrial asset management is essential for the operation and maintenance of offshore infrastructure. Whilst a concentrated focus is being held on ground-up platforms with the ability to complete inspection on air, land and sea [110,251,312–315]. Development in the cyber physical system space for offshore infrastructure is in development with many articles focussing on cyber security as identified in Figure 4-11A. As a summary, some key publications include monitoring for oil spills [316], development of cyber physical systems for inspection submersible robots [317] and security for maritime assets [290].

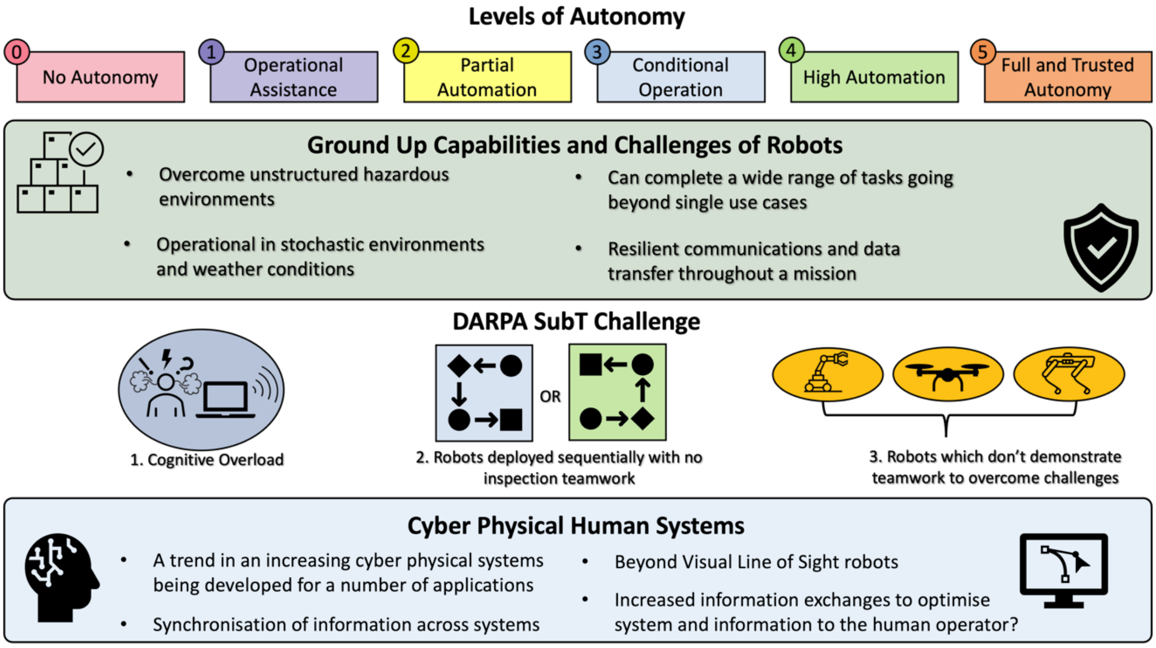
4.4. Summary of Mobile Inspection Robots

In summary, this chapter provides an overview of the state-of-the-art in mobile inspection, maintenance, and repair robots where it transitions to the leading multi-robot fleets and cyber physical systems applications: an overview can be observed within Figure 4-12.

Since the environment which robots are deployed in can be hazardous, unstructured and present stochastic variables to robots, it can be identified that improvements in ground-up capabilities such as manoeuvrability, perception, navigation and decision making are essential to ensure robots consistently achieve their mission. A key challenge with a ground-up perspective includes designing robots to complete well defined tasks such as inspection of subsea cables, wind turbine blades and routine inspections of gauges. This has resulted in a wide range of robots being tested in well-defined use cases. However, these approaches do not address challenges in scalable robotics or how to overcome resiliency issues when the 'ideal' conditions are presented to the robots. Issues in scalability include how to deploy several robots as part of a fleet via fleet management and resilience issues can include when a robot breaks down in the field requiring maintenance. This would become especially difficult to maintain should a couple of robots in the field become disabled resulting in an additional burden for the human workforce in terms of conducting inspection/maintenance tasks the robots are unable to do and conducting maintenance on the robots.

The DARPA SubT challenge demonstrates several key contributions to the field in terms of showcasing the robotic and autonomy required to overcome very difficult terrains in a BVLOS mission. In addition, improvements in wireless communications are addressed where many teams utilised ‘droppable’ WIFI nodes to create their own mesh networks. However, the DARPA SubT challenge also identified some bottlenecks in the deployment of robotic teams with a HITL where the human operator often faced significant stress in the coordination and teleoperation of the fleet. The human often had to keep extremely focused and verify the potential detection of artefacts at the same time resulting in significant cognitive overload and stress. With respect to IMR robots once they reach the phase of scaling to MR-fleets this would be represented in cognitive overload in verification of inspection/maintenance and coordination of the robots in starting or run-time of a mission. Therefore, opportunities exist to improve the experience and interactivness for the HITL. A second opportunity was identified in the DARPA SubT challenge where many of the robotic teams, whilst they were part of a team, didn’t necessarily act as a coordinated team during the mission. Whilst several teams demonstrated multi-robot SLAM maps and other methods of reduced data intensive mapping, many of the robots simply conducted navigation and artefact detection as individual robots feeding back to the HITL. Whilst some robots did represent elements of teamwork such as a robot acting as a WIFI hub via an optical cable for other robots and teamwork in terms of an operational robot shunting itself into another robot to free a stuck robot. This presents the challenges of unstructured terrains/environments and opportunities for robotic teams to overcome the challenges due to randomised variables and stochastic environment [9]†.

The results from the literature review segments led to the analysis of cyber physical systems to identify how to address robots operating BVLOS in the field with the visualisation of results from the robots for the HITL. A bibliometric search was conducted to identify key areas of cyber physical systems and identify the sectors which are developing the state-of-the-art in the field where opportunities and the state-of-the-art is discussed for each sector. The search identified an increasing number of sectors utilising the advantages from cyber physical systems related to robotics, sensors and monitoring infrastructure. However, challenges include how to create a single interface to include a range of systems and minimising operator overload from an interface which may provide a lot of information at the same time.



- Overcome unstructured hazardous environments
- Operational in stochastic environments and weather conditions
- Can complete a wide range of tasks going beyond single use cases
- Resilient communications and data transfer throughout a mission

- A trend in an increasing cyber physical systems being developed for a number of applications
- Synchronisation of information across systems
- Beyond Visual Line of Sight robots
- Increased information exchanges to optimise system and information to the human operator?

Figure 4-12 A Summary of key findings within chapter 4.

5. Methodology – Symbiosis

Symbiosis is bioinspired within nature occurring regularly as portrayed in Figure 5-1. An example of mutualism includes clownfish and sea anemones with a symbiotic relationship. The clownfish finds shelter among the anemone's tentacles which have stinging cells within however the clown fish is immune to. In return, the clownfish defend the anemone from predators, benefiting both partners. The relationship between sharks and remoras is an example of commensalism in the ocean. Remoras, small fish with specialised dorsal fins, attach themselves to sharks using suction cups. They benefit from the easy transportation and access to leftover prey from the shark's meals, gaining a free ride and a steady source of food. In contrast, the sharks are generally unaffected by the presence of remoras and do not seem to be harmed or significantly impacted by their hitchhiking companions.

Symbiosis in nature is regularly applied and can be identified in many instances within humans too. However, to date there has only been low levels of symbiosis in robotics. This thesis aims to identify these challenges and use symbiosis to overcome this to accelerate the deployment of robotics and increase their operational efficiency.

Symbiotic relationships concern formal and informal relationships which can be applied to robotics and autonomous systems and can also be compared with Cooperation, Collaboration and Corroberation (C^3). For human-robot systems, the service delivery and integration of human to robotic and autonomous systems requires carefully strategies to enable we achieve trusted autonomy, augmented learning processes, problem solving and decision making

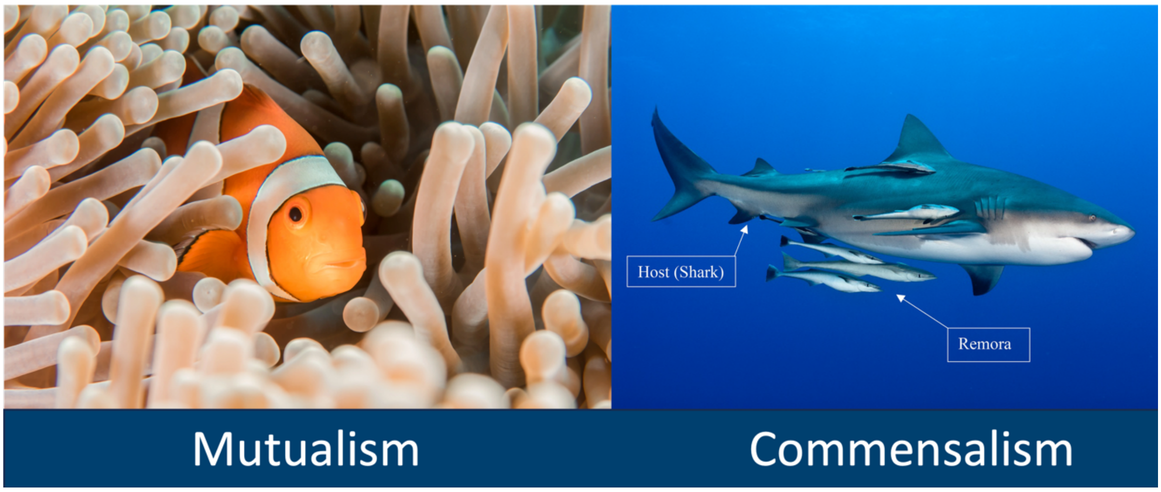


Figure 5-1 Examples of symbiosis in nature. Left- Clownfish and Anemone. Right- Shark and Remora fish.

thoguhot the deployment of systems. These technologies typically only include one element of C^3 as displayed in Figure 5-2. To address these capability gaps for robotics and artificial intelligence, we design and develop a methodology to build upon C^3 governance of robotics. This ensures that autonomous systems are safe, resilient and reliable to operate in proximity to humans and infrastructure and collaborate effectively with each other during BVLOS operations.

5.1. A General Overview : Mutualism, Commensalism and Parasitism

Symbiotic interactions occur across symbiont and host. We define a symbiont as a system element requiring a type of interaction between another system to operate. A host is defined as an element with a resource required by the symbiont. A summary of the most basic examples of symbiosis in robotics are listed where Table 5-1 displays the basic topology [319,320]:

Mutualism creates a positive outcome when both the symbiont and host collaborate. Examples of this often include the interaction between a human and robot; where the human benefits due to the automated robot completing tasks, and the host benefits as the human can advise the robotic platform of operations.

Commensalism occurs when the symbiont receives a positive result and the host is unaffected. An example would be an AI language tool improving human efficiency but receiving zero benefits or learning in return.

Parasitism is represented by interactions between technologies, which compete for the same resource, such as power. This typically occurs when there is a mix of legacy and new systems where the symbiont benefits at the expense of the host. An example includes where a robotic platform (symbiont) connects to a host to recharge its battery to complete a mission and leaves the host with a reduced capacity and unable to complete its own mission.

Table 5-1 Symbiosis typology and fitness outcome [320].

Type of Interaction	**Fitness Outcome**	
	Symbiont	**Host**
Mutualism	Positive	Positive
Commensalism	Positive	Neutral
Parasitic	Positive	Negative

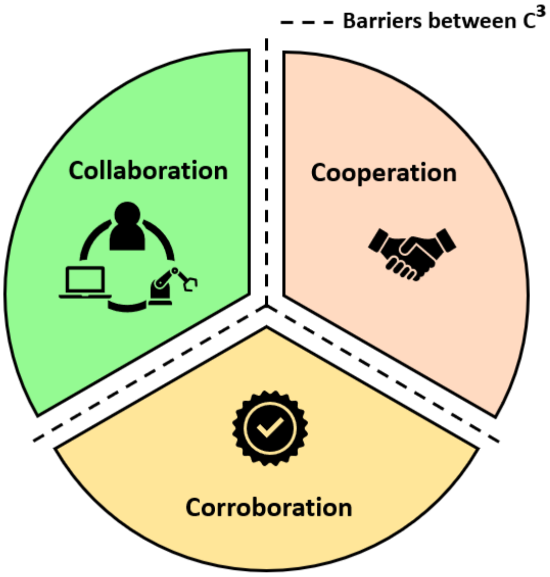


Figure 5-2 Barriers to achieving symbiosis across systems [10]†.

5.2. Robotics Focussed: Mutualism, Commensalism and Parasitism

With a focus on robotics, symbiotic interactions concern informal and formal relationships that operate under C^3 governance. In human-robot systems, it is the integration of human and RAS/I service delivery that creates interconnected strategies in trusted autonomy, augmented learning processes, problem solving and decision-making. Symbiotic interactions include the interrelationships between the symbiont and host; we define a symbiont as a system element which requires a type of interaction between another system element to operate.

Mutualism is when both the symbiont and host benefit, creating a positive outcome. Examples of this often include the interaction between a human and robot; where the human benefits due to the automated robot completing tasks, and the host benefits as the human can advise the robotic platform of operations.

Commensalism is defined by the symbiont receiving a positive result with the host unaffected. An example would be an AI bot improving human efficiency but receiving no benefits in return.

Parasitism is represented by interactions between technologies, especially when there is a mix of legacy and new systems, which compete for the same resource, such as power. This may result in the symbiont benefitting at the expense of the host. An example is where a robotic platform (symbiont) connects to a host to recharge its battery to complete a mission and leaves the host with a reduced capacity to complete its own mission.

With respect to current state-of-the-art technologies which exist in real-world deployments robots are either teleoperated, defeating the autonomous purpose of the robots, or operate within their own well defined autonomous missions with no elements of data sharing, teamwork or collaboration. This work seeks to address this challenge which inhibits the acceleration of RAS where elements of mutualism, commensalism and parasitism are presented.

5.3. Symbiotic System of Systems Approach and Robotics

The aim of a Symbiotic system of systems approach aims to address challenges in resilience, reliability, safety and productivity for multi-robot fleets. This can influence a myriad of sectors including offshore, energy infrastructure, medical, construction and logistics. We define symbiosis as the lifecycle learning and co-evolution with knowledge sharing for mutual gain (Figure 5-3). This will address challenges in human collaboration to facilitate trust for autonomous missions which require a HITL. This will also address challenges in how to improve autonomous systems overview to classify mission status, self-certification and data sharing. The drivers of this work include creating an enhanced operational situational awareness via increased bidirectional knowledge exchanged within the system of systems to optimise performance and encourage life cycle development. This can be completed by aggregating information from across infrastructure, environment, robots and HITL.

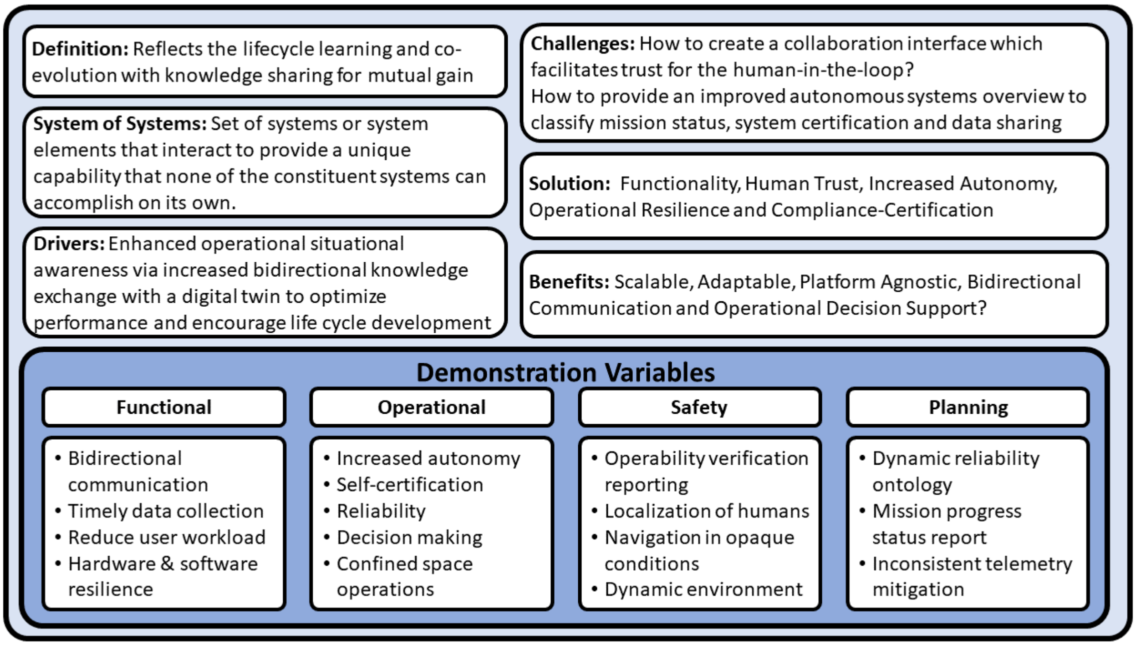


Figure 5-3 A description of a SSOSA highlighting the key definitions and descriptions [10]†.

The research direction of a symbiotic approach is displayed within Figure 5-4 which highlights two tiers which define the current state-of-the-art and future robotic deployments. Tier 1 is named *‘Adapt and Survive’*, highlighting a transition from local to global hierarchal steps in the symbiotic digital ecosystem. The illustration includes individual subsystems which can self-organise as a team and emerging trends towards robotic teamwork to complete mission objectives via C^3 governance. This aims to improve the efficient operation of individual robotic elements with overall addressment of system wide safety, reliability and resilience with a holistic approach. The continuation of design and development of a Symbiotic Digital Architecture (SDA) will result in new priorities via common behaviours to drive the evolution towards the second tier *‘Adapt and Thrive’*.

‘Adapt and Thrive’ is driven by enchanced knowledge distribution for the HITL observer through a recommender system for multi-robot objectives within an autonomous mission envelope. The cyber physical systems deployed can assess and monitor for unforeseen circumstances and model potential scenarios and make suggestions to further optimise the mission. This allows for identification of new mission priorities, chaotic missions from stochastic variables are dealt with leading to resilient evolution of the mission. A symbiotic partnership across cyber physical systems and human operator enables further elements in mutualism but can also feature parasitic elements however, not at the expense of another robot within the fleet.

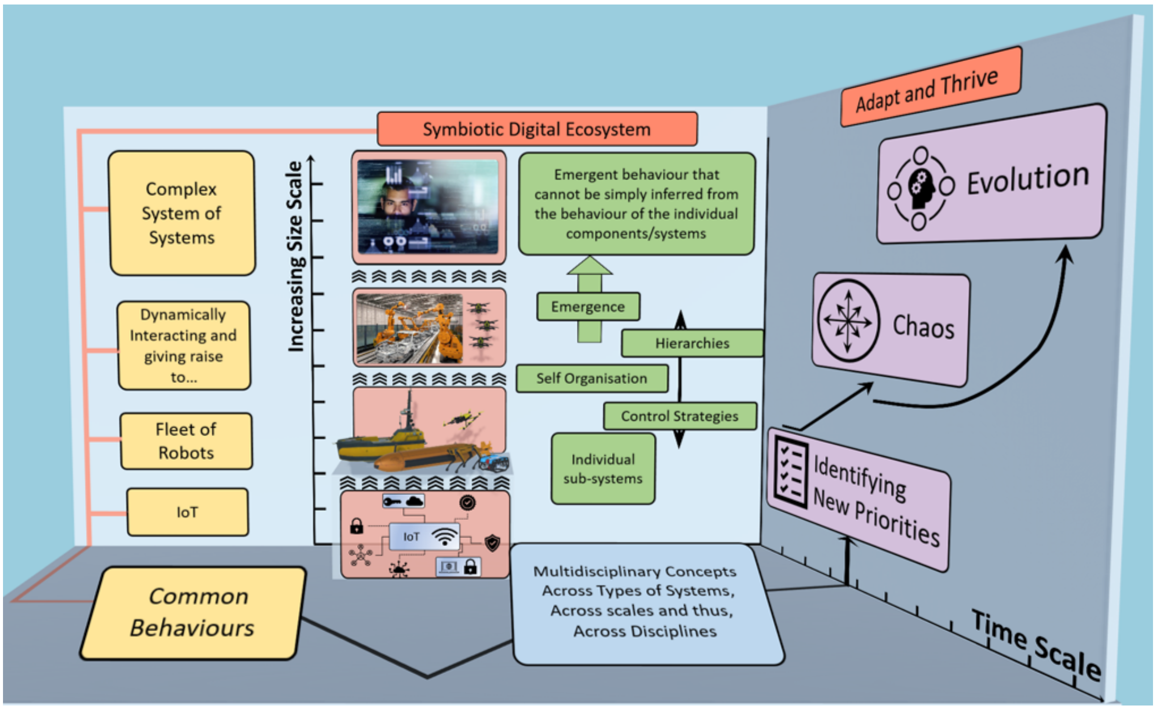


Figure 5-4 Symbiotic Digital Ecosystem with hierarchical steps required to achieve in the integration of C^3 governance.

5.4. Symbiosis Applied to Multi-Robot Fleets

There are opportunities for symbiosis to occur across a heterogeneous robotic fleet to share workload via teamwork, leverage robotic capability to access more areas during an inspection and share information to a HITL observing the mission at a digital twin. This is represented within Figure 5-5 where the HITL can access a digital ecosystem connected via a cyber physical system. This allows for the following benefits:

Platform Agnostic- Software which enables for the seamless integration of robotics to connect, communicate and operate a heterogeneous multi robot fleet alongside symbiosis which enables for robots to perform C^3 governance.

Multimodal Sensing- A wide range of modular sensors which can be easily integrated onboard robotic platforms for inspection, maintenance and repair activities.

Remote Intervention- HITL access to make suggestions to the robots within the robotic team and the ability to completely intervene for safety reasons or to teleoperate a robot directly.

Multi-Robot Fleet- A wide range of robotic capabilities within a robotic team to enable for a wide range of capabilities to be used to ensure an optimised autonomous robotic mission.

Mission Resilience- The ability for a human, autonomy or robotic platform to perform C^3 governance to allow for the robotic team to continuously have the ability to operate.

This will reduce the likelihood of mission failure, avoid robots getting stuck in extreme environments and ensure the correct operation of the fleet.

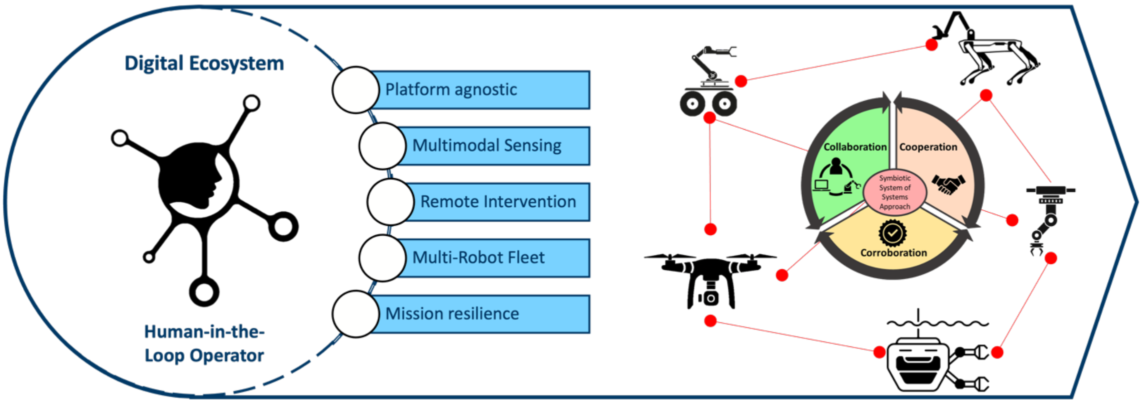


Figure 5-5 Symbiotic System of Systems Approach linking HITL via the digital ecosystem to the robotic fleet.

To date, there have been several developments in ground-up capabilities of robotics and autonomous systems with respect to capability. This includes robots which can traverse on wheels, legs, fly and swim. Robotic capability has also improved due to the development of sensors and actuators inboard, including motors, LiDAR, manipulators and other sensors. However, the motivation of this work has been to utilise a top-down approach to improve the state-of-the-art in robotics and autonomous via human facing features by addressing coordination, robotic fleet operations and robotic teamwork leading to increased safety, reliability and resilience. This is presented as discussed previously in chapter 3 via Figure 3-3 where there are shared elements of improvements in both top-down and ground-up approaches via verification and validation, communication, autonomy and function layers.

6. Introduction to the Robotic Fleet

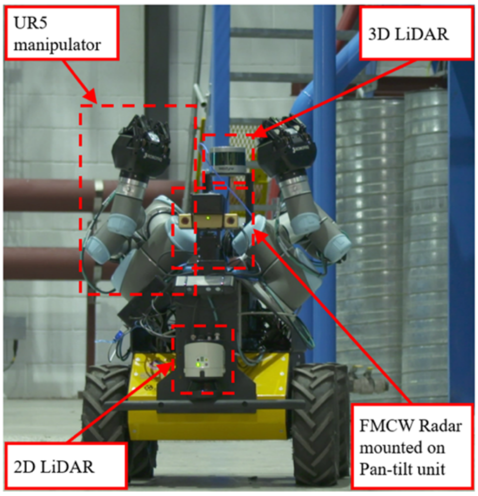
This section presents the different robots utilised in this work to provide an overview of each of their equipment and sensing capabilities ahead of the SMuRF deployments for offshore renewable energy and nuclear sector use cases.

6.1. Dual UR5 Clearpath Husky A200

The Clearpath Husky robot is a Canadian wheeled ground based robot which utilises ROS and can be deployed in a wide range of extreme terrains including snow, sand and tarmac. The robotic platform utilises a scalable and modular architecture to readily customise the platform to suit a range of mission requirements. The base of the robot can operate for a maximum operational duration of 3 hours with the ability to carry payloads of 50kg. Other key specifications of the robot can be viewed in Figure 6-1. This high payload capability enabled for the adaptation of the robot to include two Universal Robot (UR) manipulator arms to be installed onboard, leading to advanced robotic capabilities within inspection and maintenance. Low pipework and other low obstacles were identified as risks in safety for this robotic platform, therefore a 2D SICK LiDAR was mounted on the front bumper of the robotic platform and a 3D LiDAR was mounted above the body of the platform. This enabled improved navigation and safety when conducting autonomous missions. A stereo camera was also mounted onboard a pan tilt unit and, in addition, a Frequency Modulated Continuous Wave (FMCW) radar sensor was also installed above the stereo camera as displayed in Figure 6-1. However, this was later repositioned onboard one of the UR5 manipulator arms to increase accuracy in inspection missions. The FMCW radar was utilised for asset integrity inspection and is discussed in Chapter 8.

Table 6-1 Key information about actuators and sensing payloads onboard the Clearpath Husky robot.

Equipment	Key Information
2x UR5 Manipulator arms	Payload of 5kg, reach radius of up to 850mm
3D LiDAR	Velodyne Puck VLP-16
2D LiDAR	SICK LiDAR (SICK LMS-111)
FMCW Radar	K-Band Radar sensor for asset integrity inspection
Wireless Transceiver	2x Ubiquiti Bullets (AC) Connevcted using airMax Protocol



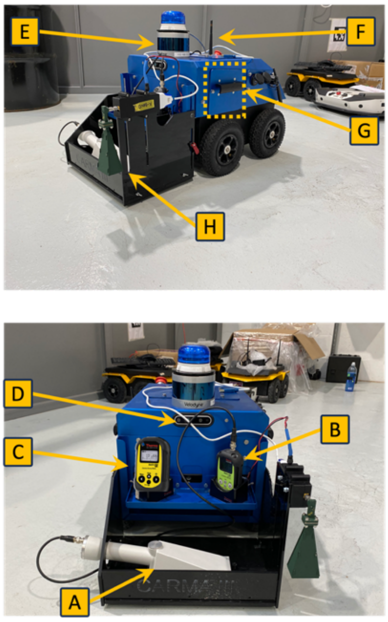
Husky A200 base	
Specification	Value
Max Speed	1.0m/s
Run-time	3 hours
User Power	5V, 12V and 24V fused at 5A each
Drivers and APIs	ROS Melodic, ROS Kinetic, C++ Library, Mathworks
Weight	50kg
Max Payload	75kg
Operating Temperature	-10-30°C
IP Classification	IP44 (IP55 also available)

UR5 Manipulator Arms	
Specification	Value
Payload	5kg
Reach radius	850mm
Degrees of Freedom	6 rotating joints
IP Classification	IP54
I/O Power Supply	24V 2A in control box and 12V/24V 600mA in tool
Temperature	0-50°C

Figure 6-1 Dual UR5 Clearpath Husky robot alongside annotations for each sensor [10,221]†.

6.2. Clearpath Jackal (CARMA II)

The Continuous Autonomous Radiometric Monitoring Assistant (CARMA II) displayed in Figure 6-2 is an autonomous ground vehicle that is created via a commercial-off-the-shelf platform (Clearpath Jackal). The objective of the robot is to continuously inspect and map the ground for contamination from fixed or migrating radioactive sources [124,321]. CARMA II utilises a wide range of onboard sensors to extend the platform beyond the



CARMA II	
Specification	Value
Base Platform	Clearpath Jackal
Max Speed	Up to 1.0m/s
Run-time	Up to 4 hours
User Power	5V at 5A 12V at 10A 24V at 20A
Drivers and APIs	ROS Kinetic
Weight	25kg
External Dimensions	450 x 500 x 400 mm
Internal Navigational Sensors	Four wheel encoders and a single IMU

Sensors Onboard Platform		
Label	Specification	Information
A	DP8 Sensor Paddle	Sensor for radiation
B	RadEye SX connected to a DP8 probe	Ground Radiation Detector (Alpha, Beta)
C	RadEye G10	Gamma radiation sensor
D	2x Intel Realsense D435i Depth Camera	Navigation
E	Velodyne VLP-16 LiDAR	Primary sensor used for navigation
F	CARMA Antenna	2.4GHz Encrypted WiFi
G	Battery Drawer	Enable for easy removal and charging of battery
H	FMCW Radar Sensor	Ground Integrity Inspection for aqueous materials

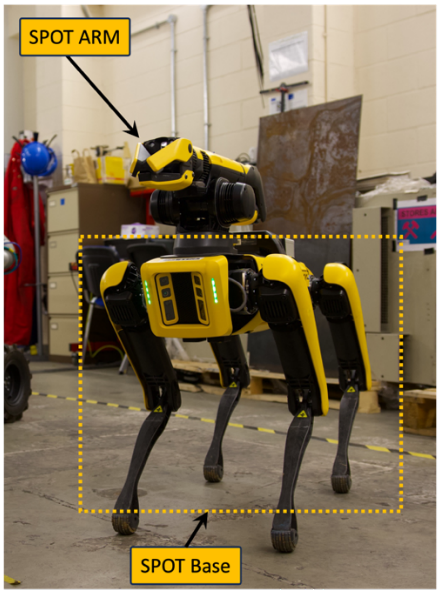
Figure 6-2 CARMA II robot alongside the specification of the robot and additional onboard sensors [322].

commercial-off-the-shelf platform (sensors onboard platform). The DP8 sensor paddle is positioned close to the ground to ensure the accurate detection of radioactive materials and to ensure that the robot does not drive over the radiation to avoid the risk of spreading radiation throughout a facility [322].

6.3. Boston Dynamics SPOT

Quadruped robots enable for extended access in extreme and cluttered environments. The walking motion of the robot enables the platform to step over obstacles, which most wheeled and tracked robots are unable to achieve. This enables the robot to access a wide range of areas such as stairs, narrow corridors and traverse over areas such as caves and urban environments.

The quadruped robot implemented within this research consisted of the SPOT equipped with SPOT-ARM to enable additional manipulation tasks to be achieved beyond typical inspections (when the robot does not have the manipulator). The SPOT robot utilises a Python Software Development Kit (SDK) which is used for the programming of the autonomous functions and mission. The Boston Dynamics SPOT is a versatile quadruped robot with the ability to navigate unstructured environments, perform inspection and carry a range of payloads to contribute to these inspections. The key features of the robot include its mobility, stability, obstacle avoidance and the ability to handle different terrains [323,324].



Boston Dynamics SPOT Base	
Specification	Value
Length	1100mm
Width	500mm
Default walking height	610mm
Min walking height	520mm
Weight with battery without arm	31.7kg
Max speed	1.6m/s
Ingress Protection	IP54
Operating Temperature	-20 to 45 C
Max step height on flat ground	30cm
Operational run-time	90 minutes

SPOT ARM	
Specification	Value
Degrees of Freedom	6 + Gripper
Length at full extension	984mm
Max. reach height on robot	1800mm
Max endpoint speed	10m/s
Weight including gripper (excluding base)	8kg
Lift capacity	Up to 11kg
Continuous lift capacity at 0.5m extension	5kg
Ingress Protection	IP54
Drag capacity (on carpet)	Up to 25kg
Integrated Sensors	Time of Flight, 4K RGB

Figure 6-3 Boston Dynamics SPOT robot and specification of base platform and SPOT ARM [324,325].

6.4. Agile X Scout and Scout Mini

Agile X robots include four wheel drive robots for indoor and outdoor applications in industrial environments. The robots are presented within Figure 6-4 where the mini robot includes smaller wheels and a smaller platform when compared to the scout 2.0. For the purposes of the investigation discussed further in this thesis, the robots were each deployed with a Velodyne Puck VLP-16 LiDAR for navigational purposes. The Scout robot offers a 15km run-time in comparison to a 10km run-time with the mini [326,327].

6.5. DJI Tello Drone

The DJI Tello drone is a compact, agile and lightweight quadcopter UAV which was implemented within the multi-robot fleet presented in this thesis. Despite its small size, the drone has several features onboard which improves its flight and has a wide range of sensors onboard as displayed in Figure 6-5. The robot offers opportunities to inspect areas at height and within confined spaces via its 720p camera which can also be used to remotely teleoperate the robot [328]. Finally, the drone can be programmed via Python enabling the robot to be integrated alongside a dashboard to coordinate different robots.

Agile X Scout Mini		
Specification	Information	Additional Sensors
Dimensions	612 x 580 x 245 mm	Velodyne VLP-16 LiDAR
Weight	23Kg	
Speed	3m/s	
Protection Level	IP22	Intel RealSense Camera
Payload Capacity	50kg	

Agile X Scout 2.0	
Specification	Information
Dimensions	960 x 699 x 349 mm
Weight	68Kg
Speed	1.5m/s
Protection Level	IP22
Payload Capacity	50kg

Figure 6-4 Agile X Scout Mini and 2.0 specification alongside additional information of sensing payloads [326,327].

DJI Tello Drone	
Specification	**Information**
Weight	Approx. 80g
Dimensions	98 x 92 x 41 mm
Built-in Functions	Range Finder, Barometer, LED, Vision System, 2.4GHz WiFi, 720p Live View
Port	Micro USB Charging Port
Max Flight Distance	100m
Max Speed	8 m/s
Max Flight Time	13 mins
Max Flight Height	30m

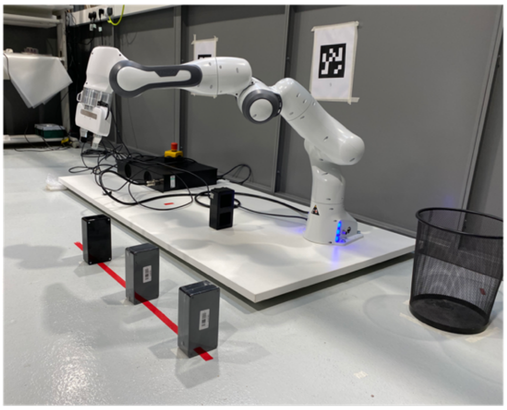
Figure 6-5 DJI Tello UAV and specification of the robot [328].

6.6. Franka Emika Panda Manipulator

The Franka Emika Panda is a collaborative robotic manipulator arm which can be used to conduct research on control and motion algorithms, grasping strategies, machine learning and interaction scenarios. The robot features rapid low-level bidirectional communications via hand and arm [329]. Force and motion sensors are implemented as standard on the robot so the robot arm has increased safety features including obstacle and detection, and reponse to unexpected contacts via immediate safety stop. The robot can be operated via C++, ROS and MoveIt alongside its interface [177].

6.7. Limpet Sensor

The Limpet sensor is a low-cost sensor which operates via magnet or adhesive for inspection or condition monitoring of offshore energy platforms. The orange protective housing acts as a shell to protect the inner circuitry as displayed within Figure 6-7. The system utilises ROS



Emirka Panda Arm	
Specification	**Information**
Degrees of Freedom	7
Payload	3Kg
Maximum Reach	855mm
Weight	17.8Kg
Protection Rating	IP30
Power Consumption	Max 350W Typically 60W
Interfacing	Ethernet (TCP/IP)

Figure 6-6 Emika Panda Arm displayed on the left in a select and sort mission with specification on the right [329].

LIMPET Sensor	
Specification	Information
Accelerometer	Inclination, Collision, Vibration, Free-Fall Detection, Movement Acceleration
Gyroscope	Tilt Detection, Orientation
Temperature	Ambient Temperature, Over-Heating, Fire Detection
Humidity	Relative Humidity
Microphone	Speech Recognition, Noise Cancellation, Audible Fault Detection
Pressure	Ambient Pressure
Hall-Effect	Locating Pipelines, Corrosion Detection
Optical	Ambient Light Intensity, Local Communication, Colour Detection
Distance (Time-of-Flight)	Fault Detection, Proximity, Collision Detection, Object Identification

Figure 6-7 Limpet sensor positioned on pipework with specification on the right [330].

and can be used to inform on information about the system it is attached to via various information presented in Figure 6-7 [330].

7. Practical Investigation

7.1. Symbiotic System of Systems Design for an Autonomous Robot in an Offshore Wind Farm Substation

80% of costs in offshore wind farm operations and maintenance is attributed to arranging and deploying personnel to site offshore [10]†. A future trend exists leading to robotic platforms which operate residentially onboard the assets which they inspect however, barriers exist in ensuring run-time safety compliance, reliability and resilience for BVLOS operations. These challenges are accelerated in offshore environments due to harsh environments which feature known and unknown risks alongside difficulties in wireless communications to ensure trusted robotic deployments.

In this subsection, the first autonomous deployment mission is conducted in a training facility which was used to resemble an offshore substation environment. The Dual UR5 Clearpath Husky robot was deployed with the aim to conduct a fully autonomous inspection mission for corrosion via the FMCW Radar sensor [10]†. The environment replicated the unstructured environment which a robot would have to face including complex arrays of pipework and cabling alongside large infrastructure systems. Whilst the mission area was sheltered from the outside weather conditions, the environment and ambient conditions posed wireless telemetry challenges. To mitigate risks in loss of wireless communications for the BVLOS mission which also occurred in hazardous areas such as a confined space, a wireless base station was created and paired alongside wireless transceivers onboard the Clearpath Husky robot.

7.1.1. Methodology

The facility represented a highly challenging environment for sensing and high accuracy for navigational sensors. The environment consisted of many obstacles around the transit route. The objective of this autonomous mission was to implement the first stage of a Symbiotic System of Systems Approach (SSOSA) that utilises a SDA to enable for the orchestration of enabling technologies via a cyber physical system and provides a useful system of systems overview. The key themes presented in this autonomous mission evaluation included the ability to overcome safety, resilience and reliability challenges where the SDA (displayed in Figure 7-1), supports the co-evolution with knowledge exchange and lifecycle learning across interconnected systems.

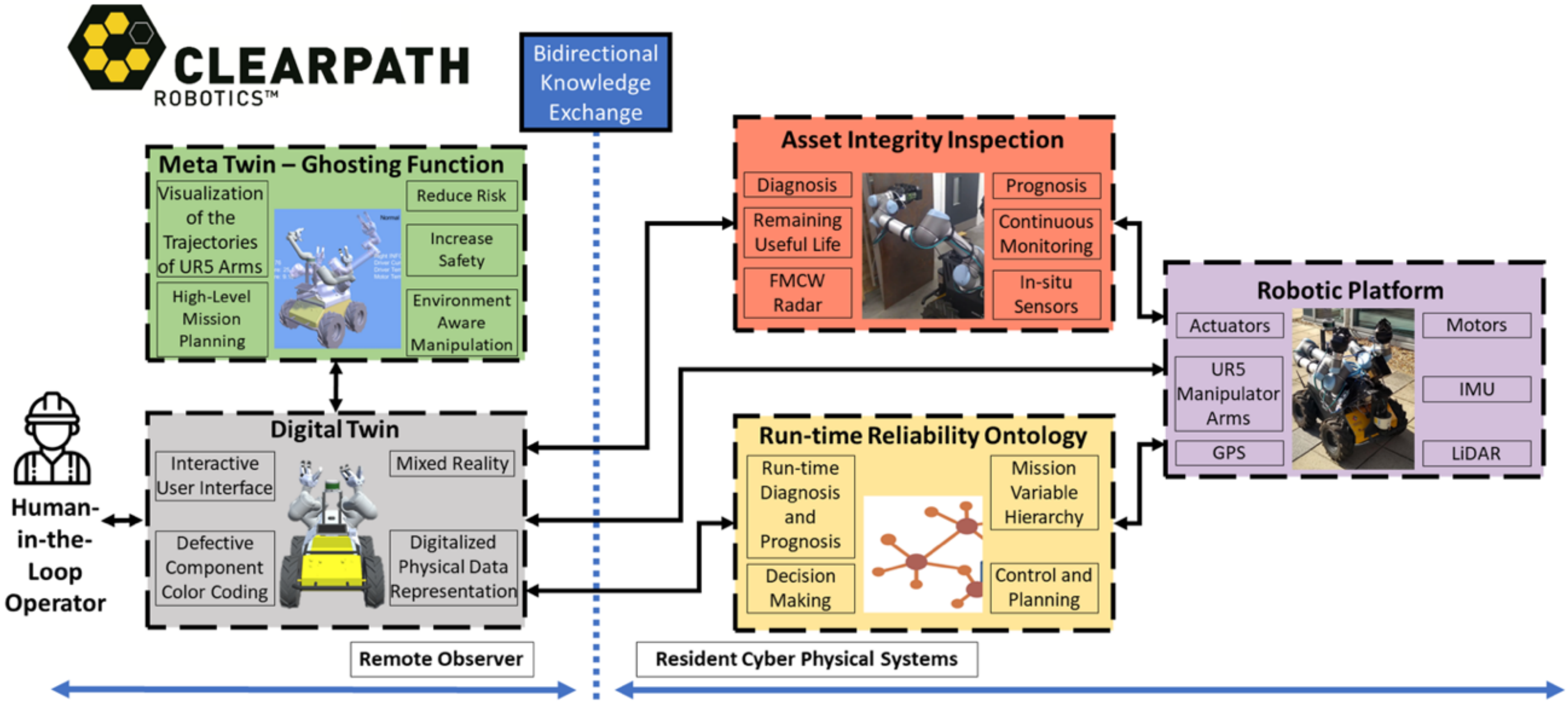


Figure 7-1 A symbiotic cyber physical architecture presented for a single robot with linked subcomponents deployed in the field connected with a HITL accessing a digital twin [10]†.

For information to be actionable within a time critical context, it must be mapped into a design for resilient systems through our SDA, as in Figure 7-1, which further highlights the functional, operational, safety compliance and planning requirements, and enables resilient symbiosis between a range of systems that are *intra* to robotic systems and *inter* between other robotic platforms. The SDA incorporates the systems engineering which allows the implementation of up to 1800 different sensors and actuators within our architecture [10,331]†§.

Trust is a vital qualititive measurement when any human interacts with a system, therefore our SDA commences with the HITL linked to the digital twin of the robotic platform. This allows for the remote human observer to attain actionable information via bidirectional communications from the interactive graphical user interface. This information can be displayed via mixed reality devices (depending on user preference, ability and experience) leading to an enhanced hyper-enabled situation report or via laptop. Information about the robotic asset and mission is represented as a digitally generated model in real-time with information such as components which may be displaying defects and represented via intuitive colour coding on the digitalised model. Of key importance is to ensure the user does not experience cognitive overload from the digital twin dashboard therefore information should be fed in a logical manner and at the right time to the user to reduce stress [332].

The digital twin also includes a meta-function named the ghosting function whose objective is to reduce risks and hereby increase safety in the manipulation activities the Husky robot conducts. When the HITL interacts with this segment of the DT, they can visualise the trajectories of the arms via a simulation ahead of committing to the trajectories on the real robot; reinforcing trust and assurance in remote BVLOS operations.

The purpose of the deployment in this autonomous mission was to conduct and retrieve information via asset integrity inspection of the analogue substation environment via structural health monitoring for corrosion [37]†. To enable this, a FMCW radar module was deployed as a payload onboard a pan tilt unit on the front of the robot as displayed previously within Figure 6-1 for non-destructive evaluation. This novel deployment of the FMCW radar sensor provides detection and classification of corrosion precursors without the requirement for contact at the surface where the corrosion occurs. This advances the state-of-the-art in structural health monitoring and also has further use cases discussed within Chapter 8.

7.1.1.1. Run-Time Reliability Ontology

To enable transformative front end resilience, decision making, near to real-time diagnostics and prognostics, a reliability ontology was designed and implemented onboard the robotic platform. The aim of this system was to support the human operator in understanding the diagnostic information from the autonomous ground vehicle and preventing detrimental effects on the robot related to state of health and remaining useful life of the robotic platform. This would ensure the reliability of critical subsystems during a mission and have the ability to autonomously minimise the risks during a mission. The ontology feeds front-end data analysis and edge analytics to back-end models within the DT. This included data from actuators and motors which are then translated into actionable information within the DT when passed through the ontology. The AI-driven ontology supports increased responsiveness to ensure the self-certification of the robotic platform during run-time [333–335]§.

For the run-time reliability ontology a diagnosis automaton was created for each critical system of the robotic platform, for example, motor, motor driver, battery, wheel, single component or an integrated device. This can include information for sensed and non-sensed results. This is due to a segment of a system having its own distinctive states to ensure that it operates optimally and to ensure its operating within set boundaries [334].

$$\textit{States} = \{\textit{sensed, possible, normal}\} \tag{7-1}$$

$$\textit{Sensed states} = \{\textit{low current, high temperature, ...}\} \tag{7-2}$$

$$\textit{Possible states} = \{\textit{broken, aging, degrading, abnormal behaviour, ...}\} \tag{7-3}$$

$$\textit{Normal states} = \{\textit{on, off, ready, working, ...}\} \tag{7-4}$$

Different events can alter the state of different components onboard the robotic platform and have an effect on the autonomous mission. These states can consist of external, spatial, temporal and internal conditions and can consist of expected events with different degrees of results. Event transitions are classed as:

$$\textit{Events} = \{\textit{internal, time-driven, space- driven, external}\} \tag{7-5}$$

Hierarchical relationships are used to define all of the models within the reliability ontology. These consist of *'is-connected-to'*, *'is-linked-to'* and *'is-type-of'*. For example, *'system x is connected to system y'*.

$$\textit{Binary relationships} = \{\textit{Implication, causality, prevention, hierarchical, composition, optional, aggregation}\} \tag{7-6}$$

The ontology articulates the logic inherent to the binary relationship, facilitating C^3 integration across the subcomponents within the SSOSA framework. A detailed overview of the logic is described fully by Zaki *et al.* [334].

'Causality', *'implication'* and *'prevention'* are the three binary relations and are combined in modality to show the degree of certainty in the relationship. For example, x *must-cause* y, x *might-cause* y. Modal verbs combined with those in relation include:

- *Could* (less possible)
- *Might/may* (possibly)
- *Should* (very likely)
- *Would* (really certain)
- *Must* (absolutely certain)

Each segment has its own properties which can affect the intra-inter relationships between the parts of the system such as : *'reusability'*, *'validity'*, *'dependency'* and *'availability'*. For example, x (is) reusable, x (is) valid, x (is) available. In summary:

1. For each critical part of the system a diagnosis automaton is created.
2. Describe the transitional relationships between states.
3. Describe the binary relationships between the states in different components or,
4. Build the hierarchical model of the robotic system.
5. Build the generic model of the components.

Complexity and scalability of the ontology presented in this research are the key metrics. For the ontological complexity of the implemented system, the space requirements are approximately 25 times the size of the raw data with a linear relationship observed between these two variables. Initially, the connection between ontology size and reasoning time demonstrates an exponential trend. However, once the ontology size reaches a threshold of around 3MB, the correlation shifts to a linear pattern, with the reasoning time stabilising at approximately 15 milliseconds [334].

7.1.1.2. System of Systems Integration

An illustration of the different layers and subcomponents which were implemented during the autonomous mission is presented within the system integration process in Figure 7-2. This diagram highlights the various systems and highlights areas of symbiosis and C^3 of data to enable the system. The layers down the left side display the links between all subsystems and highlight the mission variables being addressed. The human interaction layer represents where the HITL can interact with mission components within the DT. The DT is presented as the user interface containing the functions and tools for the human operator to interact with the robotic system and receive an overview of the mission status. The DT is directly linked to the FMCW radar sensor used within the confined space inspection mission. The decision-making Planning Domain Definition Language (PDDL) layer of the run-time reliability ontology is linked to the software and hardware on the robotic platform. This means it is linked to the SLAM stack, motion planning and ontology. The ontology processes diagnostic information received from the internal sensors onboard the autonomous system. The SLAM stack receives data from the LiDAR sensors and cameras. For the mobile base and manipulators, the motion planning layer calculates the information to achieve this.

The system integration process results in increased resilience in the overall system as each subcomponents when operating individually, would be unable to resolve the solution

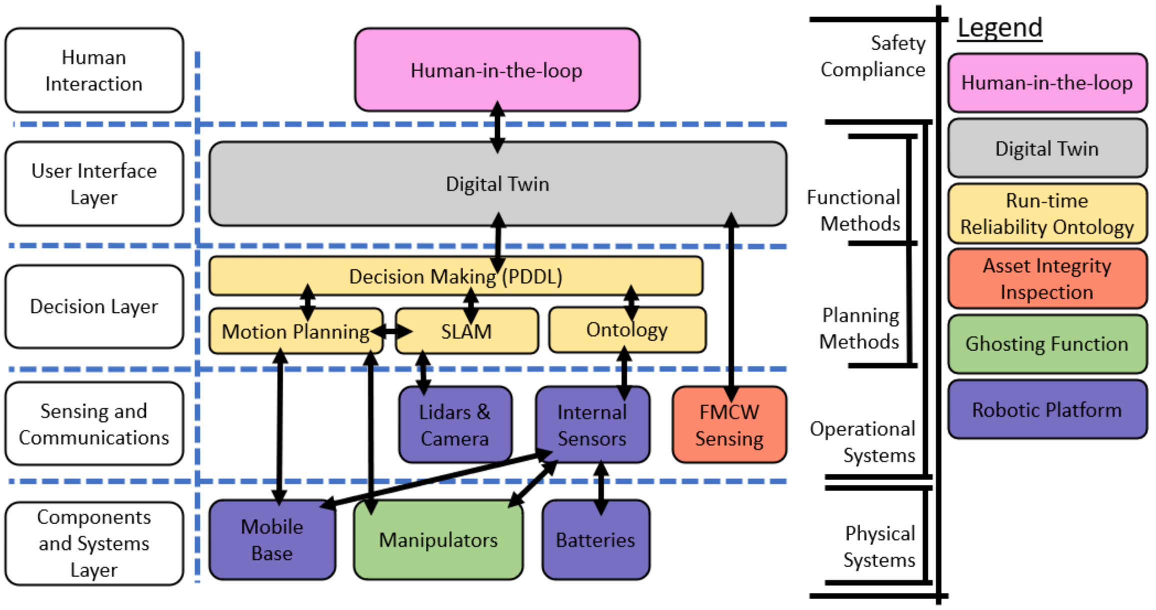


Figure 7-2 The integration of the different subcomponents presented in Figure 7-1 utilised during the autonomous mission evaluation [10]†.

required. C^3 governance across all acting systems enables for mutualistic symbiotic relationships to be achieved. This work focuses on the integration of the top-down requirements, as well as the ground-up capability challenges to support resilient autonomous missions.

7.1.2. Autonomous Mission Envelope

The autonomous mission was partitioned into eight different phases each containing key waypoints to ensure the execution of an asset integrity inspection where a summary video can be accessed [336]§:

A. Pre-mission planning
B. Mission start at home position
C. Transit to asset integrity position 1
D. Perform asset integrity scan 1
E. Transit to asset integrity scan 2
F. Perform asset integrity scan 2
G. Transit to home position
H. Mission end

Alongside the key mission waypoints, three major system issues were included to simulate symbiotic collaboration dynamics including the necessary requirement for symbiotic reassessment of the mission by the robotic platform, intra-inter system self-certification and adherence to safe operational protocols. This enabled validation of the *'adapt to survive'* paradigm, where the mobile platform requires symbiotic AI-assisted decision-making in a commensalistic manner with a system reliability ontology to ensure adaptability with dynamic environmental conditions. As identified within the literature review, this ensures the robotic asset has the ability to:

- Identify barriers or threats via integrated sensing which may result in an unsuccessful mission or add too many risks to the safety case.
- Bidirectional knowledge exchange via collaboration with a DT system to relay results from asset integrity inspection to inform parallel robotic elements and the HITL operators during run-time.
- Enhanced decision-making validation and reliable autonomy achieved by leveraging AI and/or the HITL operator through wireless communication with minimal latency.

A key aspect of this investigation was to demonstrate the resilience whilst the mobile platform operates autonomously within a safety compliant autonomous mission envelope.

C^3 within the SSOSA methodology provides real-time HITL awareness and symbiotic C^3 governance between the systems that allow the robotic platform to operate.

This section presents a confined space asset integrity inspection which also assesses resilience and reliability of the mobile platform via randomly induced faults onboard the robotic platform during the mission. The reliability ontology facilitates the ability for the robot to self-certify its onboard systems and decide whether mission termination is the best option if necessary. The environment where the robotic platform was deployed can be visualised via the illustration in Figure 7-3 where key waypoints can be displayed for the asset integrity segments of the mission and the confined space area which the robot was to navigate.

The overall mission envelope for the Clearpath Husky A200 with dual UR5 manipulators is presented within Figure 7-4 as a function against symbiotic interactions and mission duration. In general, symbiotic interactions are low when the mission is going according to plan however, symbiotic interactions increase when the robot requires other systems to help to overcome a challenge. For example, this can be represented as asset integrity inspection or self-certification when faults are induced. The dashed grey line displays the mission if no faults were to occur (the mission goes as planned) the orange dashed line (inset) displays

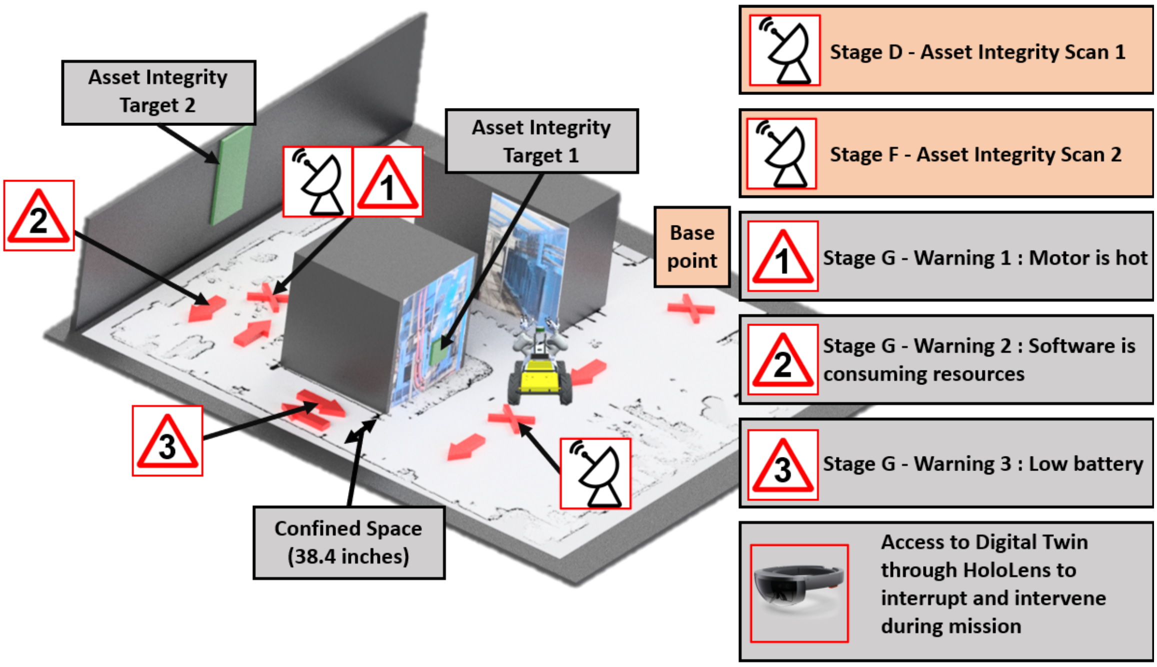


Figure 7-3 The autonomous mission envelope overview presented using a 3D model of the industrial environment highlighting key events during the mission route completed by the Dual UR5 Husky A200 [10]†.

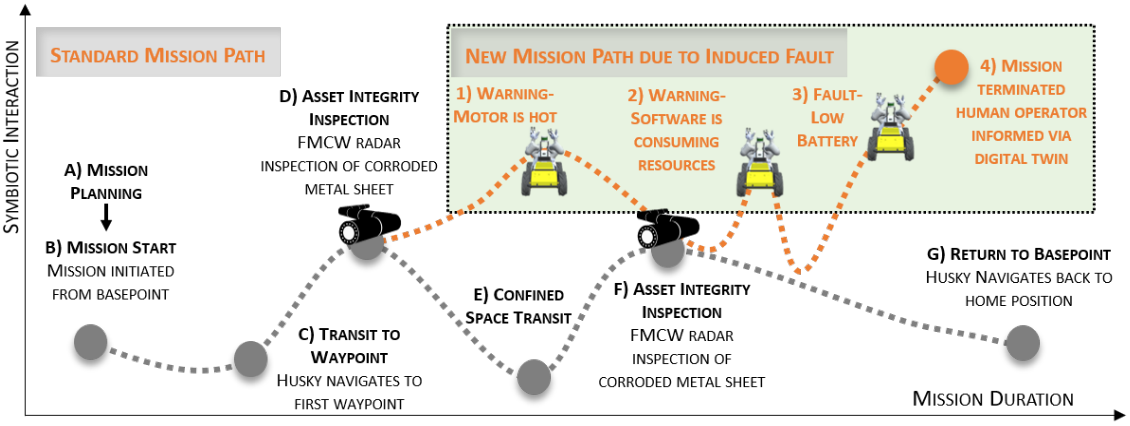


Figure 7-4 A-G represent key stages during the standard asset integrity mission path. (Inset) 1-4 represent system warnings and faults which were induced on the mobile robot resulting in autonomous symbiotic interactions to occur or the safe recovery of the robotic system via mission termination [10]†.

increased level of symbiotic interaction acting as a result in the induced/simulated faults onboard the robotic platform resulting in altered mission path, demonstrating the SDA response and recovery strategy.

An itemised description and analysis of the autonomous mission envelope can be accessed within Table 7-1 resulting in a breakdown of the autonomous mission. The applied methodology of the SSOSA can be viewed within Appendix 13-1 as a flowchart for the operations, symbiotic decisions and interactions across the subsystems. A breakdown of what occurred during the autonomous mission for each waypoint follows in the next subsections.

Table 7-1 Eight identified stages within the asset integrity inspection for the mobile robot in a confined space mission [10]†.

Mission Event			**Challenges**			
Stage	**Objective**	**Description**	**Functional**	**Operational**	**Planning**	**Safety**
A	**Pre-mission planning**	Inspection area recon	Human operation of robotic platform to map op-area	Remote control operation onsite	Access required for human and robot	Onsite safety of human and robot
		Confined space asset integrity mission	Operator positions waypoints on map with tasks to complete	Human interaction with DT to create mission	Operator requires good knowledge of plant and mission to create mission	Is the robotic platform suitable for the environment?
B	**Mission start at base point**	System idle awaiting orders	Wireless connectivity between DT and robotic platform	Reliable wireless communications	Basepoint approved as safe	Self-certification from robot that it is fully deployable

			to receive orders from operator			
C	**Transit to asset integrity scan 1**	Navigation to Asset inspection 1 waypoint	Navigation and mapping	Husky computes most efficient route to complete mission	Accessible waypoints selected by human operator	Safety compliance with environment, humans and infrastructure
D	**Perform asset integrity scan 1**	Asset inspection 1	Manipulator positioned for FMCW radar asset inspection	Requires sufficient clearance for maneuver	Direction of scan input by the human operator within the DT	Safe distance from infrastructure adhered to
E	**Transit to integrity scan 2**	Confined space operation section	Proximity detectors warn of collision risk with structure	Continuous navigation through confined area	Requires platform to plan optimal route	Increased risk of navigational error or collision with infrastructure
F	**Perform asset integrity scan 2**	Asset inspection 2	Manipulator positioned for FMCW radar asset inspection	Requires sufficient clearance for maneuver	Direction of scan input by the human operator within the DT	Safe distance from infrastructure adhered to
G	**Return transit to base point**	Warning 1: Motor is hot	Motor in danger of failure	Reduced mobility Decreased power	Reprioritise mission objectives	Increased risk of loss, mission incompletion or collision
		Warning 2: Software is consuming resources	Managing the limited computing resource	Drain on computational efficiency (processing power)	Ontology decision-making whether to reprioritise mission	Robotic platform in danger of loss or stranding
		Warning 3: Low battery	Reduced current available for systems	Limited time to complete mission	Robotic platform removes objectives from mission plan	Robotic platform in danger of loss or stranding, incomplete mission
H	**Mission End**	Scenario 1: No warnings detected by reliability ontology - Mission success	Real-time bidirectional communication, Synchronisation with DT	Robotic platform completes mission and returns to base point. Updates operator of successful mission	Robotic platform updates synthetic environment to apply acquired data to next mission plan	Ontology never detected any risks therefore risks are minimal
		Scenario 2: Some warnings detected - Mission success	Real-time bidirectional communication, Synchronisation with DT to allow HITL to advise/overlook decision-making	Robotic platform completes mission and returns to base, Updates operator of successful mission and warnings to be considered	Ontology decision-making must be set to continue under the severity of those warning conditions	Integrity of the robotic platform could be compromised but mission still achievable

		Scenario 3: Many warnings detected by reliability ontology - Robotic platform stops to ensure integrity of asset is maintained- Mission Failure	Real-time bidirectional communication, Synchronisation with DT to inform HITL of faults and impose recovery of platform	Robotic platform stops at current position where warning occurs to prevent failure. Mission incomplete	Ontology decision-making must be set to failure under the severity of those warning conditions	Integrity of the robotic platform is compromised and unable to complete the mission. Platform is required to be recovered by human or another platform

A. Pre-Mission Planning

For any autonomous mission, pre-planning is essential to ensure mission success. However, for confined space autonomous missions, this becomes more critical to ensure the safety of infrastructure and equipment which, if collided with, can have serious detrimental impacts, e.g., resulting in explosions or toxic release of gases. Ahead of deploying the mobile robotic platform autonomously, a reconnaissance mission was performed to map the area accurately where the human operator teleoperates the robot. This also enabled for the human operator to have an improved understanding of the environment and allowed for improved decisions when deciding where waypoints should be placed for the robot in its autonomous mission, see Appendix 13-1A for more details. ROSPlan was utilised for the planning once tasks were assigned to the robotic platform [337].

For the demonstration a waypoint planner (ROS navigation and planning stack) was utilised to create the autonomous mission for the dual UR5 Husky robot. Decision making, based on PDDL, ensured sequential system actions were achieved where the robot completes the assigned tasks by the operator [338]. Waypoint goals are positioned and passed to the navigation stack by the planner where the SLAM data is utilised for accurate navigation. ROS move base handles the movement between the waypoints. The DT provides interaction for the operator to create the waypoints for the mission. It is essential during the reconnaissance mission that an accurate map is created to enable the waypoints to be accurately positioned resulting in the successful deployment of the robotic platform.

B. Mission Start at Basepoint

Once the reconnaissance mission is completed, the robot is now available to be deployed autonomously to conduct the required inspection mission. To start, the robot remains idle at the approved base point (mission start) until triggered by the human operator. This requires reliable wireless connectivity between robot and DT. However, should be very likely as the basepoint will definitely be within good range as it will be an allocated safe position for the robot to start. Once the mission is triggered, the robot actively self-certifies its onboard systems via watchdog nodes which are subscribed to diagnostic data from the run-time reliability ontology. This ensures the robot is visible as deployable via the DT for the human operator. The DT operates as a real-time collaboration hub, where the methodology is presented in Appendix 13-1B. The robotic platform calculates the most efficient route to perform the mission via the navigation stack.

C. Transit to Asset Integrity Scan 1

A low level path planner alongside SLAM was implemented to allow the robot to reach the first waypoint. A live version of a local constmap is updated alongside a global costmap to ensure the safe operation of the robot during the autonomous mission. The global costmap represents the map generated in the planning phase. The local costmap represents data collected live from the LiDAR systems to ensure that any changes in the environment are detected and avoided. Within the map created by both global and local costmaps, grid cells are marked as *'clear'* or *'occupied'* using points detected by the LiDARs. This results in corroborative navigation to reduce risks associated with autonomous navigation. The PDDL planner outputs a waypoint goal action containing x, y and θ positions as an input to *move_base* for navigation (see Appendix 13-1C for details).

D. Perform Asset Integrity Scan 1

The first inspection is carried out at this waypoint and includes the deployment of the FMCW radar sensor for non-destructive analysis for corrosion. The K-band sensor collects data from the metallic sample for around 30 seconds where multiple scans are taken with each chirp lasting 300ms over a frequency sweep of 24-25.5GHz. Challenges in achieving the successful scan include maneuvering the robot safely, avoiding collisions with the nearby infrastructure and ensuring the robot is within a safe distance of the target for inspection. The mission objective is presented in Appendix 13-1D and displays the C^3 governance, where mutualism is achieved for both the robot and human operator due to the robot ensuring the sensor is orientated and positioned correctly.

E. Transit to Asset Integrity Scan 2

This transit includes navigation through the confined space with narrow entry as indicated in Figure 7-3 where the maximum width measured 38.4 inches. This resulted in a constricted area which had minimal clearance on each side of the robotic platform, resulting in regions of increased collision risk. The path parameters of the robot were tuned to allow for higher performance during this phase whilst still maintaining collision avoidance.

F. Perform Asset Integrity Scan 2

Upon arrival at the second waypoint, the robotic platform performs the asset integrity inspection autonomously. The challenges as presented in Table 7-1 are comparable to the initial asset inspection waypoint, and ensure safe maneuvering of the manipulator arms and of the robotic platform (Appendix 13-1F).

G. Return to Basepoint

To validate the mission performance for overcoming challenges in resilience and reliability, three faults were induced in the mission via additional code activated within the core of the robot. The induced faults were designed to increase in severity with the final fault resulting in the ontology terminating the mission. The key induced failures are displayed in Figure 7-3 (grey segment of legend) and Table 7-1. The successful detection of faults and resulting warnings to the HITL is part of the significant findings within this demonstration. This qualitatively improves the resilience in the systems as this information is passed through the SDA to the DT. Overall, this enhances the operational overview for the HITL due to the autonomous detection of onboard faults via the ontology. The resulting self-certification of the mobile platform and knowledge exchange to the DT for the remote operator enables faults to be detected earlier and a reduction in the risk that a robot will overload any systems resulting in damage of the system.

A formal representation was utilised for the detection and identification of faults to support run time diagnosis of the autonomous system. Different sets of semantic relationships and diagnosis automata to model the system result in the ontology formalism. The elements are made up of top-level between components, or at bottom-level between the different states of the components. The diagnosis automaton is created for each critical part of the system and can be used for stand-alone or integrated devices whether the results from each system are sensed or un-sensed [334]. The ontology mutualistically assesses the state of health of the robotic platform via designed threshold states. If a warning is detected, the ontology relays the results via C^3 governance to the human operator. For example, if a warning is presented to the human operator via the DT, the robot will most likely have decided to continue the mission, however, the operator can still remotely terminate the mission. In a second scenario a fault threshold may be reached, therefore the ontology will automatically terminate the mission and update the HITL [10]†.

In this research we recognise that continued use of robotic systems will mean they develop malfunctions and faults within their systems. Consequently, our objective is to detect anomalies or invalidities in the system during operation (under stress). The end objective of the run-time reliability ontology is to verify that the robotic behaviour matches the specification of the robot; resulting in corroboration. We design four test considerations in our mission evaluation:

- A possible problem in a non-sensed component, e.g., a wheel.
- Prediction of a component, e.g, a low battery.
- Root cause analysis of two components negatively affecting a third.
- Prediction of a high temperature in the motor driver.

Three warnings are induced in the system alongside the challenges and presented in Table 7-1G Appendix 13-1G. The run-time reliability ontology prioritises fault thresholds over warning thresholds to ensure the correct action is taken to reduce risks in the integrity of the robotic asset. The system integration is discussed next for each specific warning [10]†.

Warning 1 is detected by an increasing motor temperature towards a preset warning threshold. However, the increase in temperature is within a designed threshold and so is still functional. The relationships which represent the designed classification of warning and fault thresholds are presented in Appendix 13-2, algorithm 1 and 2. During the mission evaluation, when the warning threshold occurs as described in algorithm 2, a warning message notifies the human operator within the DT to provide them with the information that the motor temperature has started to overheat and could affect the mission if this continues. At this time during the mission this motor temperature is only within the warning threshold, and not the fault threshold which is higher, therefore the autonomous mission continues and the human has the option to terminate the mission or allow the robot to continue [10]†.

Warning 2 relates to computational process management which is identified via management of the limited computing resources available on the robotic platform. This could result in other data processing and control being delayed in the event of too high processing durations and therefore errors; resulting in a parasitic robotic platform. The run-time reliability ontology utilises pseudocode in Appendix 13-2, algorithm 3 and 4 to detect if the Central Processing Unit (CPU) or Random Access Memory (RAM) is consuming the resources. For the second time during the autonomous mission, the HITL is prompted with a warning whilst the ontology makes the appropriate decision to continue the mission. At this stage it is important to note that both warnings 1 and 2 resulted in warning thresholds which meant that the robot could still operate effectively within a predefined threshold. Therefore, the run-time reliability ontology makes the decision to continue the mission and always offers the option to the HITL to have the final decision in whether the mission should be terminated [10]†.

Warning 3 results in a fault threshold which alerts the human operator to a low battery and state of charge. This is a critical situation for the robotic platform as reduced current availability requires replanning of mission capabilities. Within the *'Adapt and Survive'* methodology, the ontology executes the decision to prevent further deterioration to the mobile platform. As the fault threshold takes priority this results in the pseudocode for Appendix 13-2, algorithm 5 being initiated to terminate the mission. The reason for this was due to safety management planning as the integrity of the robot is compromised but the robot is still recoverable. This updates the human operator that the mission has been terminated at the DT alongside an accurate prognosis of the system status. This allows the human operator to replan to recover the robot with the remaining state of charge. This could result in remote teleoperation to ensure an efficient route back to safety as most likely the human is unable to access the confined space area without additional personnel for safety or other additional safeguards in place [10]†.

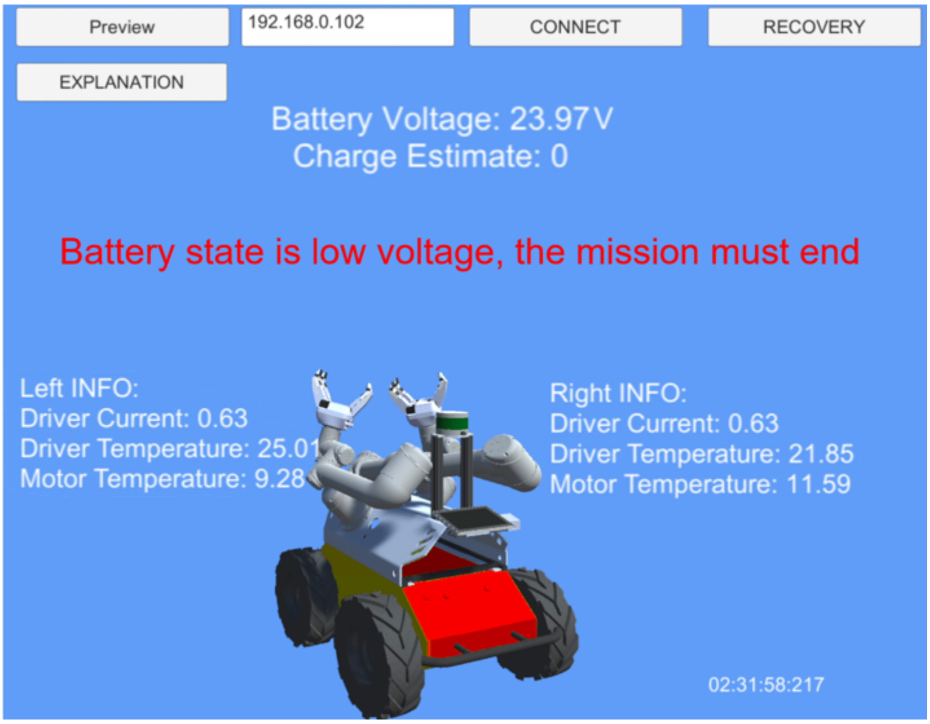
H. Mission End

Within this stage of the mission the demonstrated benefits of the run-time reliability ontology and SSOSA are presented. In summary, warnings were detected on the route of the mission during real-time, where the ontology had the option to continue the mission or terminate the mission for each consecutive error with the aim to ensure the integrity of the robot (e.g. reduce failure of components). For each detected error by the ontology, the result was presented to the HITL operator with the option to terminate the mission if they deemed it to be necessary. However, to ensure the adherence to safety governance standards created within the run-time reliability ontology, the robot has the ability to monitor its ability to operate thus ensuring continued resilience and survivability [10]†.

Whilst many warnings were collected on the route, namely warnings 1 and 2, the autonomous system remained within our designed self-certification standards however, towards the end of the mission, the mission was terminated by the reliability ontology as an error reached a fault threshold. The human was updated in real time with information displayed in the DT about the fault. The information displayed in the DT is a result of filtered ontology messages, displaying the hardware and software issues to the user via a red colour-coded alert system as in Figure 7-5. The interface was designed to draw the attention of the user to high priority areas. The DT also presents lower order information such as diagnostics from the robot. The SSOSA allows for a framework for coordination, adjudication and integration of all subcomponents, systems and the HITL goals. This has high impact for future BVLOS operations where a human operator must know the integrity of a robot which is operating potentially kilometers away in real-time which will require wireless communications and a DT to verify the state of the robot [10]†.

The presented taxonomy in Table 7-2 discusses the analysis of the mission performance via the symbiotic safety compliance modes regarding the motor temperature of the mobile platform. Each safety compliance mode is selected according to their specific C^3 governance requirements including system awareness, provision, operation and outcome, corresponding to Mutualism, Commensalism and Parasitism (MCP) that occurs in the mission evaluation. The SDA relies on these relationships to be created across the blocks which make up the architecture (reminder within Figure 7-1). System awareness can be defined as the ability for an autonomous system to be aware of its own capabilities. For example, self-preservation without affecting the human, although the mission may have stopped, the integrity of the robot is maintained due to self-certification. In this autonomous mission envelope, commensalism is high, mutualism is moderate and parasitism is low as the robot continues the mission with a minor possibility of degradation to the robotic platform state of health.

Human error is minimised throughout the mission via the run-time reliability ontology as faults and warnings can be detected much quicker via autonomous watchdog agents. Since fault thresholds take priority over warning thresholds, these are setup so that the robot



192.168.0.102

Battery Voltage: 23.97V
Charge Estimate: 0

Battery state is low voltage, the mission must end

Left INFO:
Driver Current: 0.63
Driver Temperature: 25.01
Motor Temperature: 9.28

Right INFO:
Driver Current: 0.63
Driver Temperature: 21.85
Motor Temperature: 11.59

02:31:58:217

Figure 7-5 Error message displaying a low battery state within the DT alongside colour coded alert system in red on the mobile base indicating the status of health of the robot [10]†.

Table 7-2 Taxonomy of symbiotic safety compliance for robotic platform motor temperature [10]†.

C^3 Governance	**Safety Compliance Modes**		
	Mutualism	**Commensalism**	**Parasitism**
System Awareness	Moderate	High	Low
HITL Provision	High	Moderate	Low
Operation	Self-certification (Implication)	Augmentation (Causality)	Instructional (Prevention)
Outcome	Positive Anticipation	Indeterminacy	Negative Anticipation

terminates the mission when the unsafe operating condition is detected. Under HITL provision, the ontology. For HITL provision, parasitism is low as the ontology continuously conducts state of health monitoring of the robotic platform resulting in a mutualistic relationship between robot and HITL. Mutualism results in the shared understanding of the robotic system and automated decisions which can react quicker than the decision making by the HITL. Augmentation can occur at both information and data levels via the SSOSA. In this scenario, the HITL is prompted by various warnings and a new fault threshold terminates the mission. A balance between commensalism and parasitism can be achieved if an experienced operator was to alter fault thresholds during the mission planning phase. Commensalism occurs as the experienced robotic operator gains more from the robotic platform provided that the alterations do not negatively affect the robotic platform leading to a failure. However, parasitism can occur if the experienced operator sets the thresholds inappropriately resulting in priority of the mission over the integrity of the robotic platform leading to a detriment in the robotic state of health [10]†.

7.1.3. Scenario Modelling

Autonomous mission envelopes present a number of challenges which can be predictable and unpredictable for different types of environments therefore it is important that safety, reliability and resilience challenges are considered in depth. Due to the complexity of mobile autonomous systems, this can lead to several warnings, faults and failures which can inhibit mission success. The novel approach enables effective runtime diagnostics and prognostics. The results show that the proposed approach and modelling can capture component interdependencies in complex mobile systems. The resulting information can be processed within 10ms to support front end mitigation, inferring the scalability of the approach. In summary, three scenarios have been modelled representing varying levels of severity where scenario 3 is the most detrimental scenario to the mission and so was applied and presented to our SSOSA and SDA.

The three scenarios represented are as follows:

Scenario 1- No Warnings or Faults Detected by Reliability Ontology- Mission Success

Zero reliability issues are induced in the system. The run-time reliability ontology monitors the systems and validates the healthy state of the robotic platform. The autonomous mission runs smoothly and no prompts are shared to the human asides from standard mission reporting (asset integrity inspection and waypoints completed on the route).

Scenario 2- Warnings Detected Only – Mission Success

The ontology detected thresholds in the system which resulted in warnings however, had not yet reached failure modes. The mission is still achievable as the robot is still operating within its designed thresholds. The ontology converts this data into actionable information for the HITL who is prompted with the warning information but continues the mission. This allows the operator to determine if there is too much risk associated relative to the environment or future terrain. For example, if the motor is within warning threshold at a terrain angle of 20 degrees and the HITL knows the terrain reaches 30 degrees (thus meaning more stress on the motor) then they may choose to terminate or deviate the mission to reduce the risk of reaching the failure threshold.

Scenario 3- Many Warnings and/or a Major Fault Detected by the Reliability Ontology-Autonomous Mission Termination

Firstly, several warnings may result in cognitive overload meaning the HITL chooses to terminate the autonomous mission due to too much information leading to confusion. Secondly, if severe faults are detected by the run-time reliability ontology this allows for evaluation that the robot operates within resilience, reliability and safety compliance in keeping with the objectives of this investigation. Where this scenario occurs this results in an example of parasitism within a mutualistic collaboration facilitating more stable operation. This would be as a result where the mission terminates to ensure the integrity of the platform for future missions.

7.1.4. The Digital Twin within a Symbiotic Architecture

A digital twin is defined as ‘digital replication of living as well as non-living entities that enable data to be seamlessly transmitted between the physical and virtual worlds’ [339]. This section reports a ‘stage 4’ DT, as presented in Figure 7-6, which leverages edge-processing in real-time to predict future behaviour with extended data analytics and simulation capabilities. A DT designed to this standard enables for positive interdependencies across internal and external functions. This allows for the integration of real-time sensor data streams and processing with other operational robotics and autonomous systems or artificial intelligence inputs and services. The DT ensures legitimacy is maintained across and within technology ecosystems.

Three main challenges for human-robot collaboration exists and are presented by Hastie *et al.* which elements of this work address including planning in human-robot teams, execution and monitoring a task and adaptability in human-robot partnerships [340] When implemented effectively, a DT can address challenges in pre-mission planning, situation reporting, the ability to assume control (via teleoperation) and the ability to resynchronise with a robot is communications are lost. Increasing levels of internet connectivity and cloud computing solutions have enabled the rapid advancement of cloud robotics [341]. The technology is fundamental to DTs and offers a powerful computing platform without the hardware costs. More importantly, it allows for easier integration and communications robots

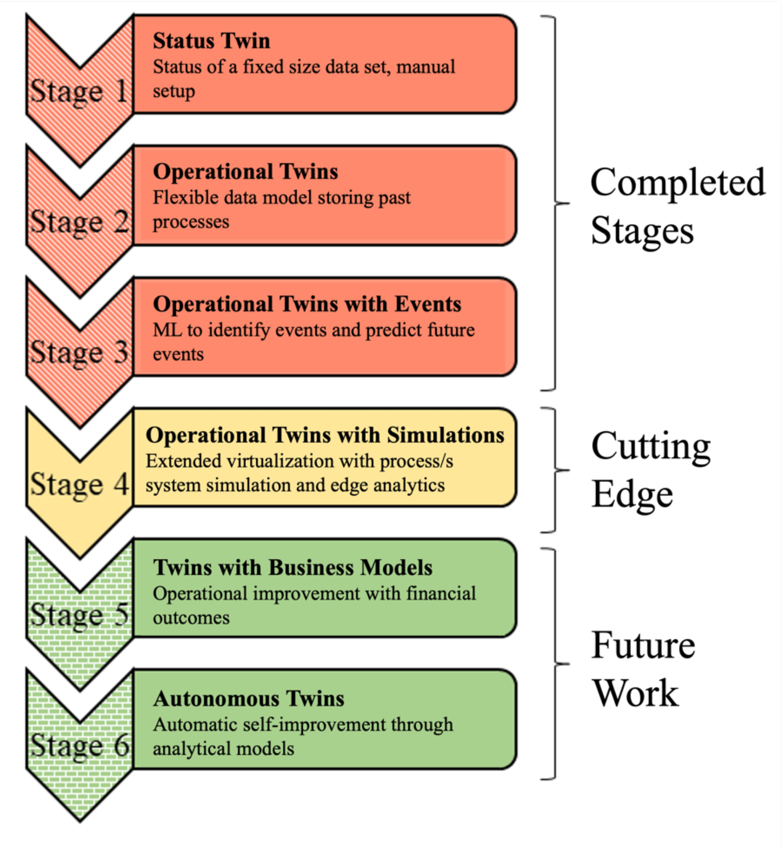


Figure 7-6 Stages of a DT indicating stage 4 as the current model presented in this chapter of the thesis [10]†.

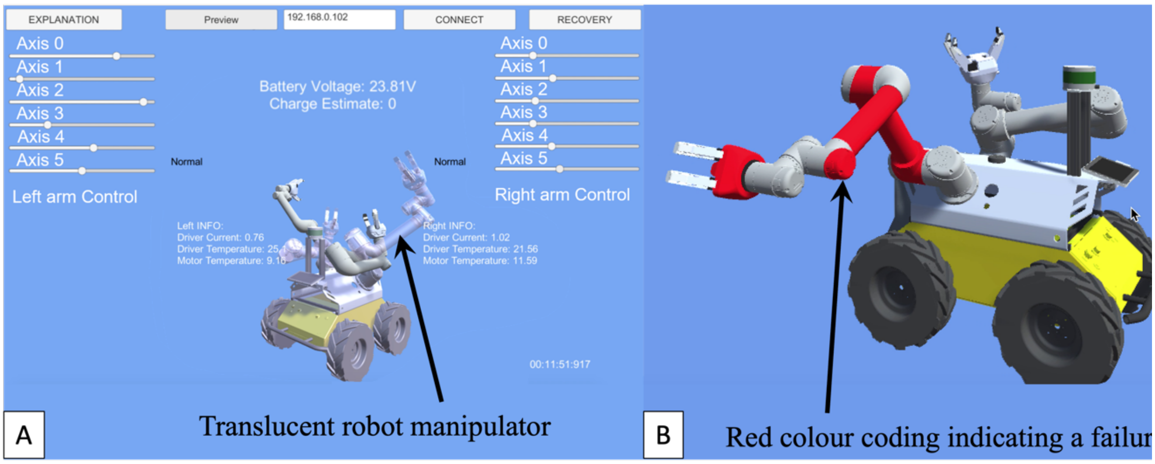
and edge-devices including human-robot interfacing. The remainder of this section described the functionality of the DT used within the autonomous mission evaluation.

7.1.4.1. Ghosting of Dual Manipulators

The mission evaluation incorporates potential for robotic manipulator capability which has high future impact in securing trusted BVLOS operations. Currently many robots navigate autonomously around areas and collect inspection data about the environment or infrastructure. The future role of manipulators will have significant impact in several sectors as robots can maneuver or carry different payloads in grippers or have the ability to change the positions of valves or switches. However, challenges to date exist in intuitively informing the operator about the status of the robotic platform and manipulators. Hence, this thesis considered collaboration features which allows the user to monitor and control the robotic manipulators in real-time. Messages generated by the reliability ontology are displayed and the user can interactively control the manipulators on the robotic platform and also mirror their real-world condition in run-time. This work increases in importance as robotics shift into more BVLOS roles [10].

A DT server package was integrated within the robots ROS core to ensure the run-time connectivity between the robot and client machine. A benefit of the method used is that the DT interface does not limit the operator to a single ROS powered machine and through the SDA an operator can connect via any device, anywhere, to the robot. The DT GUI facilitates visualisation and interaction demonstrating the core values of the SSOSA in terms of human-robot collaboration.

The ghosting function is presented in Figure 7-7A, which enables remote planning and control of the robotic manipulator. The planned positions of the robot arm are presented to the user via a translucent 'ghost' model, which allows the user to preview and analyse the operation ahead of executing the command on the real-world robot. The sliders enable for the human to interact with the robot arms to simulate each axis of the manipulators to ensure they act as intended to increase the levels of trust during operation. The DT was also evaluated for run-time fault prognosis where the arms would display red colour-coding when a fault was detected in the simulation of the movements. For the illustration presented in

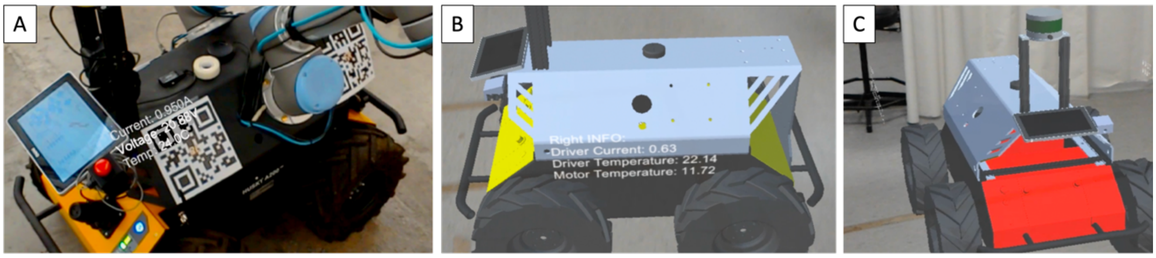


Battery Voltage: 23.81V
Charge Estimate: 0

Left INFO:
Driver Current: 0.76
Driver Temperature: 25.1
Motor Temperature: 9.16

Right INFO:
Driver Current: 1.02
Driver Temperature: 21.56
Motor Temperature: 11.59

Figure 7-7 A- meta ghosting function of the DT, highlighting the controls and translucent (ghost) robot manipulator acting as the proposed end position for the robot arm. B- Meta warning function of the DT where the arm indicates the protective emergency stop in the simulation [10]†.



Current: 0.950A
Voltage: 20.88V
Temp: 24.0C

Right INFO:
Driver Current: 0.63
Driver Temperature: 22.14
Motor Temperature: 11.72

Figure 7-8 A- Mixed reality interface showing natural language of the health tatus of the robotic platform corresponding with the QR code. B- Augmented reality interface displaying current health data of the robot. C- Augmented reality displaying red colour coded fault alert on the base of the robot [10]†.

Figure 7-7B a motor fault is induced on the simulated arm via the ROS core displaying the fault on the robotic arm in red [10].

7.1.4.2. Mixed and Augmented Reality

As the number of robots deployed in different environments increase, this will mean that humans will need to work alongside robotic platforms more often leading to increased human-robot collaborations. On-site and remote collaborations will allow for rapid state of health assessments to be made in regards to a robotic platform and can be achieved via mixed and augmented reality. Figure 7-8A presents the visualisation from a Microsoft HoloLens displaying a mixed reality interface of the diagnostic information of the robotic platform overlaid in the real-world environment via a Quick Response (QR) code. Figure 7-8B presents similar diagnostic information however this time on a fully augmented reality robotic platform where the robot is of a 3D model using the Microsoft Hololens. When applying an augmented reality robot to the self-certifcation application explored in this chapter we can via self-certification data via the robot as in Figure 7-8C to understand where errors are occurring in the robot. The colour coding can also be tailored depending on the platform and the nature of the fault too [10].

7.1.5. Results

The results within this investigation have been informed by an extensive literature review from academic and industrial sources into offshore robotics. The review identified that the predominant mode of deployment of robotic platforms for offshore wind farms use Commercial Off-The-Shelf (COTS) platforms. Short term developmental sprints and rapid deployment of COTS can be achieved for wind farm operators but this does not demonstrate a long term solution. Secondly, robotic platforms are deployed in simple, short-term missions with individual roles which does not result in opportunities for robotic teamwork or collaborations. As a result of this analysis we identified key barriers to include C^3 governance, run-time safety, reliability and resilience which are developed in this section and can advance semi and fully autonomous capabilities via a need to adapt in dynamic environments and reliability of resident robotic platforms via a cyber physical systems approach which can be enhanced within a SSOSA.

In this section we presented a SSOSA with the aim to address challenges imposed by limitations in C^3 governance, namely, operational, functional, planning and safety requirements to ensure the reliability and resilience within a mission. We present these challenges within an autonomous mission envelope which provides a run-time operational assessment of a robotic platform in an offshore wind farm analogue. Therefore, the SSOSA presents a new methodology that creates a CPS which enables for the aggregation of information across autonomous platforms, sensing, reliability modelling and human-robot interactions. This overcomes the previously discussed challenges as information can be amalgamated away from previously partitioned sub-elements into a common, synchronised DT environment. The SDA can process outputs from up to 1800 different sensors or systems leading to a hyper-enabled capability for a human observer, enhancing the visibility and increasing the ability of the autonomous system to query its operating environment and adapt its response accordingly (updating the resilience and reliability measures) [331]§.

The implementation of the SSOSA with the Dual UR5 Clearpath Husky have verified the ability that the SDA can provide accurate state of health of the robot, mission status and foresight modelling for fault precursors. Most importantly, the framework presented in this thesis, ensures safety during the transition where robots move from semi-autonomous to fully autonomous via consistent adherence to our capability criteria. Human-robot interaction is of vital importance where a DT facilitates this trust and has intrinsic value due to the flexibility and scalability, allowing for platform agnostic integration with COTS or bespoke robotic platforms.

In the presentation of the symbiotic methodology, this investigation presented the first implementation of *'Adapt and Survive'* and presented the key benefits to why *'Adapt and Thrive'* is the next vital step for persistent autonomous deployments. Adapt and survive was demonstrated as the robot was able to self-certify its systems and take an initial step to ensure the survivability of the platform without further deteriorating its systems; activating its emergency stop when a fault precursor occurred. In the future implementations of our symbiotic robotics we develop *'Adapt and Thrive'* leading to further development of resilience and reliability parameters in stochastic environments.

7.2. Cyber Physical Architecture for Symbiotic Multi Robot Fleet Autonomy

The state-of-the-art in robotic systems which are regularly deployed in the real-world is predominantly focused on individual or robotic swarms aimed at short-term, well-defined inspection, maintenance and repair missions. The deployed robots also require a dedicated team of deployed human assistants too. Robotics and Autonomous Systems has seen recent acceleration in perception [342–344], manipulation [345–347], sensing [348–350]§, human-robot interaction [351–354], planning [355,356] and distributed AI [357–359]. However, there are barriers inhibiting further adoption due to challenges in complex, dynamic and long-term missions with known and unknown challenges [360]. The design and development of a solution would enable mobile autonomous systems to create sustainable, continuous and resilient value for operators in several sectors including several lifecycle phases of offshore wind farms [20]†. This investigation focusses on the challenges within O&M where humans currently complete vital actions during IMR to ensure the ssafety, sustainability and productivity of offshore infrastructure [333,361]§. This segment further develops the symbiotic approach and applies it to a multi-robot fleet creating a novel collaborative learning strategy to address intrinsic challenges in service robots advancing resilience, reliability, productivity, safety compliance and coordination of a multi-robot fleet as displayed via full video and summary videos [362,363]†.

7.2.1. Analysis of the Challenge

In brief, we critically analyse the Cerberus team who were the winners of the Systems Challenge within the DARPA Subterranean challenge representing the leading capabilities in multi-robot fleet field robotics. The Cerberus team deployed several quadruped ANYmal robots, wheeled robots and aerial robots [279,286,287]. The DARPA Subterranean mission has been discussed earlier within this thesis as a reminder in Chapter 4.2 where this segment provides focused analysis of this team. Whilst ANYmal quadruped and aerial robots were utilised, the wheeled robot played a crucial role within the team to ensure the wireless comms were established. The wheeled robot had a wired optical fibre cable connected to the base station to ensure reliable communications to the base station during the mission. The ANYmal robots could also deploy wireless nodes to also extend communications enabling for a HITL to oversee operations. Team Cerberus; approach displayed many advantages throughout their autonomous mission envelope and are worth discussing due to the significant advancements. Firstly, the robotic team created complex shared maps of the environment. Secondly, the individual robots had the ability to explore the environment whilst connected via WIFI and whilst out with wireless connectivity. Thirdly, the robots could retrace its steps to return back to WIFI connectivity to send data to the HITL. Finally, the team aimed for reduced human interventions however, the HITL had full control to intervene and teleoperate when robots were connected via WIFI. However, there were several challenges faced by team Cerberus which inhibited further success and have informed the pathway via symbiotic interactions within the research in this chapter. We present several challenges discussed by the team and how conceptual symbiotic interactions could have helped to overcome these challenges as presented in Table 7-3 [9]†.

The next segment of this chapter shares the view that heterogeneous multi-robot fleets can improve autonomous missions in unstructured environments however, implements a SSOSA which focusses on reliability, resilience and safety via SMuRF managent and addresses similar challenges presented by Tranzatto *et al.* [279].

Table 7-3 A list of challenges identified within DARPA SubT which inspired the symbiotic approach with appropriate conceptual cybiotic interactions which could address these challenges in future [9]†.

Challenge		**Solutions via Symbiotic Interaction Concepts**
A	Team Cerberus' wheeled robot became stuck when their optical cable became tangled.	Symbiotic interactions include the ability for a robotic team to implement and deploy C^3 governance across the fleet. Where a robot in the team faces a challenge in resilience or reliability, the other robots within the team work together to identify the problem and overcome the issue. A quadruped with a manipulator arm could have identified the location of the tangled segment and used the manipulator arm to dislodge the tangled cable allowing the wheeled robot to move deeper into the mine. This would have extended WIFI capability for the team resulting in a mutualistic interaction for the robotic team.
B	WIFI nodes were inadvertently knocked over by robots during operation resulting in the mesh network being disabled.	The quadruped with manipulator arm could be used to reposition the WIFI breadcrumb nodes in the scenario where they are disconnected. This would increase the resilience of the mission and ensure the WIFI coverage to re-establish connectivity.
C	The aerial robots started their missions from the entrance gate and only covered area which had already been covered by the ground robots therefore did not score any points.	Marsupial robots to date mostly consist of deploying a aerial robot onboard a quadruped to leverage the robotic capability of each [486]. For example, aerial robots typically have short battery durations, therefore the robot could 'piggyback' a quadruped and then be deployed to explore an area the quadruped is unable to explore. This would improve the productivity of the robots and allow for deeper areas to be mapped in the subterranean environment.

7.2.2. Methodology

The design and implementation of a SMuRF results in opportunities and advantages for robotics and facility operators. Robotics for the ORE sector aims to remove personnel from hazardous environments, reduce costs with offshore logistics and the downtime of offshore assets. Within the ORE sector, several opportunities exist for a wide range of robots (UAVs, Subsea, surface, ground robots) to conduct inspection, maintenance and repair missions in these hazardous environments to reduce humans conducting work in dangerous areas. Whilst research is being conducted on ground-up approaches where each robot addresses different challenges in IMR, there are opportunities in top-down approaches which will be a vital step for operators of large infrastructure. Therefore, opportunities exist in creating an interface where a robotic fleet can be coordinated for autonomous missions. A second opportunity exists in leveraging the robotic capability across a fleet where robotic teamwork improves IMR activities or allows the fleet to adapt to unforeseen challenges in resilience or reliability via teamwork. This could include where a UAV corroborates the inspection from a quadruped or where a wheeled robot is stuck and requires a third person view from another ground robot or UAV to assess its next move.

In this subsection, a robotic fleet solution is deployed that utilises collaborative resilience to overcome the complexities associated with the interactions in multi-robot teams, critical infrastructure assets, dynamic ambient conditions, accessibility challenges of remote and high-consequence environments and optimised integration of a HITL. A SMuRF as displayed as an overview in [363]†, utilises a collaborative network within a CPSs architecture. Additional video showcases of the SMuRF can be viewed alongside key descriptions, results and the GitHub repository via the following citations by Mitchell *et al.* [364–367]†. An Operational Decision Support Interface (ODSI) allowed for the HITL to observe and interact with the deployment and organisation of the SMuRF. This was implemented to connect with a low latency, bidirectional communications to enable for the exchanging of data and information across the integrated systems and robotic fleet. The wheeled, legged and UAV robots were commanded and controlled at the ODSI in addition to teleoperation of the UAV to demonstrate the novel capabilities of the SMuRF. The novelties of the SMuRF mission evaluation included:

- Integration of three diverse robots with a single ODSI which all utilise different operating systems, programming languages and software development kits with the ability to communicate simultaneously.

- The capacity to include up to 1800 real-time systems and sensors via low latency and bidirectional communications [331]§.
- Symbiotic interactions across the robotic fleet to ensure the safety, resilience and reliability via predetermined autonomous missions.
- Improved C^3 governance when compared to the autonomous mission evaluation in 7.1 where robotic platforms can cooperate, collaborate and corroborate information across the SMuRF. This allows for validation and verification to take place ahead of autonomous decisions and humanin-the-loop interventions.
- Deployment of Machine Learning to detect and distinguish a (analogue) battery pack and robotic platform to support a symbiotic interaction to ensure resilience of a mission.

This work follows on from the applied SSOSA presented in subsection 7.1 where we aim to support the integration of distributed leaning and observations into a symbiotic assistance-based learning methodology. This also enables for strategic C^3 governance across independent systems to become part of a unique capability that is created as part of a larger system via mutualism. This results in symbiotic interactions which can be positive (mutualistic) or negative (parasitic) interactions across the SMuRF.

In advancing the examples of mutualism and parasitism discussed in chapter 5, the following advanced examples are presented:

Mutualism- An IMR mission where a MR fleet is used to leverage the unique capabilities across the mission envelope. Each robots has different advantages and disadvantages, where this positively contributes to the collection of data from robots within the inspection.
Parasitism- A mission scenario in a MR fleet where one robot benefits at the detriment of another robot. This could be to address non-intervention challenges where a robot faces a problem (due to reliability or resilience), initiating an autonomous response to address the setback. For example, as discussed previously, in the DARPA challenge example, when the wheeled robot with optical cable became stuck a quadruped robot with an arm could have untangled the cable. This would result in the detriment of the quadrupeds robotic mission status (decrease in battery life, increased processing power to complete the task, decrease in efficiency in completing original objectives).

For the ORE sector and robotics deployed within this environment, it is important to prevent loss of assets and robots in the field. In addition to minimising costs and ensuring recovery from high impact, low frequency events. This can be achieved via a multi-robot fleet and system of systems approach where interactions can be achieved in the creation of a SMuRF and hence the approach in this segment.

The field robotic laboratory included a warehouse area with enough space to deploy a number of robots within a MR-inspection mission. The environment was designed to represent an offshore substation platform as displayed in Figure 7-9A and B. The robots utilised in this mission consisted of a Clearpath Dual UR5 Husky robot, Boston Dynamics SPOT quadruped with arm and DJI Tello Drone where the strengths and weaknesses are summarised in Figure 7-10 for each platform. Finally, the key objectives of the research are presented within Figure 7-11 where we focus on safety, resilience and reliability during the autonomous mission envelope.

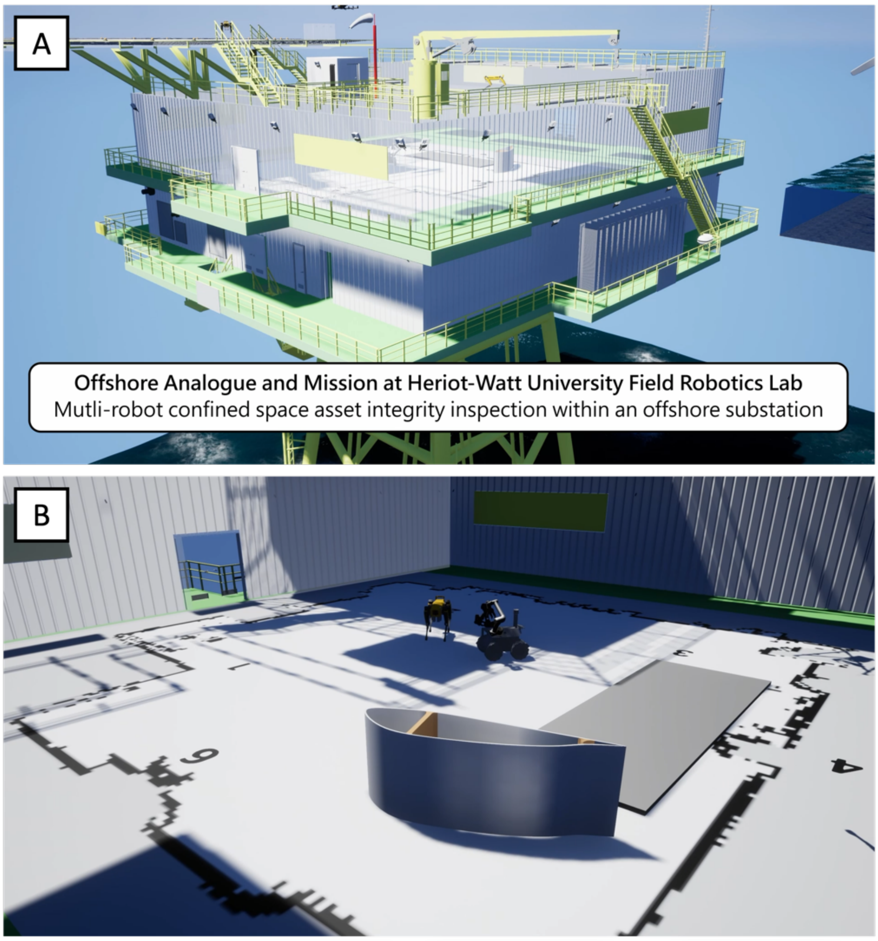
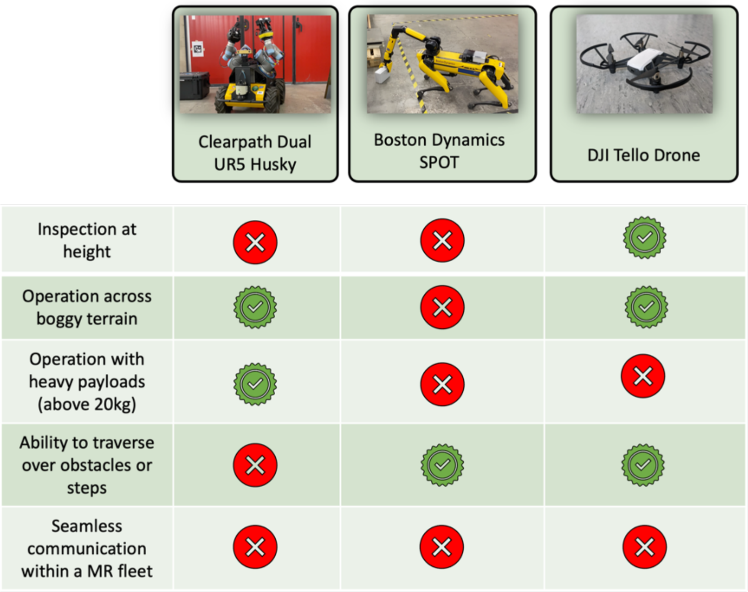
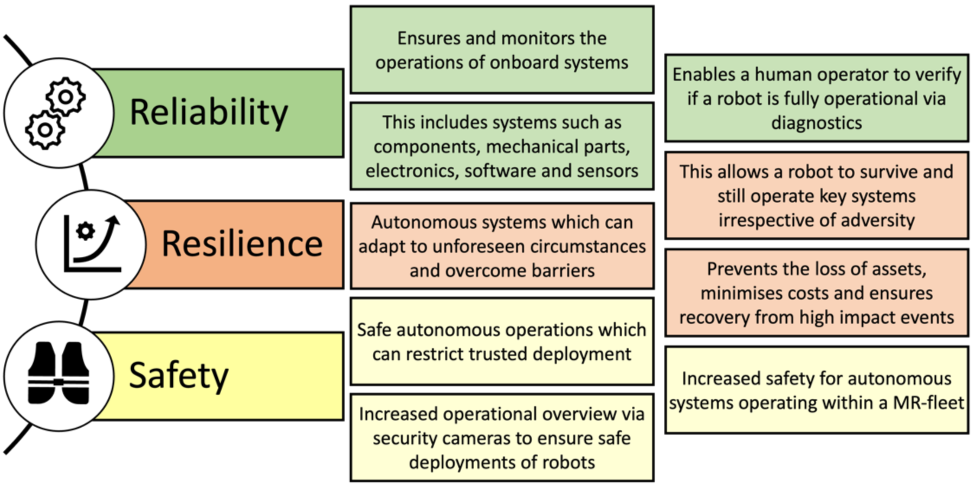


Figure 7-9 A visualisation of an offshore environment and SMuRF taxonomy diagrams (A) External view of an offshore substation used for visualisation purposes representing the field robotics laboratory.(B) The internal mission space within the offshore substation presented in (A) [368]†.



	Clearpath Dual UR5 Husky	Boston Dynamics SPOT	DJI Tello Drone
Inspection at height	✗	✗	✓
Operation across boggy terrain	✓	✗	✓
Operation with heavy payloads (above 20kg)	✓	✗	✗
Ability to traverse over obstacles or steps	✗	✓	✓
Seamless communication within a MR fleet	✗	✗	✗

Figure 7-10 The SMuRF utilised in this autonomous mission evaluation with strengths and weaknesses [368]†.



Reliability

Ensures and monitors the operations of onboard systems

This includes systems such as components, mechanical parts, electronics, software and sensors

Enables a human operator to verify if a robot is fully operational via diagnostics

Resilience

Autonomous systems which can adapt to unforeseen circumstances and overcome barriers

This allows a robot to survive and still operate key systems irrespective of adversity

Prevents the loss of assets, minimises costs and ensures recovery from high impact events

Safety

Safe autonomous operations which can restrict trusted deployment

Increased operational overview via security cameras to ensure safe deployments of robots

Increased safety for autonomous systems operating within a MR-fleet

Figure 7-11 Key objectives, evaluation and results of the CPS within the IMR mission [368]†.

In response to these barriers we have further developed our SDA as displayed in Figure 7-12 to include the coordination, cooperation and collaboration of information from a MR-fleet in near to real time across all platform types and programming languages, [10,369]§. Whilst it may seem that there is not many adaptations other than in the MR-fleet box (when compared to Figure 7-1), there should be careful considerations in how data can be minimised across the fleet and how bidirectional communications should be infused within the fleet. In our scenario all robots are connected to the DT representing the ODSI and the DT coordinates the communications across the robotic fleet. However, in future, robot to robot communications could take place for robots operating in close proximity

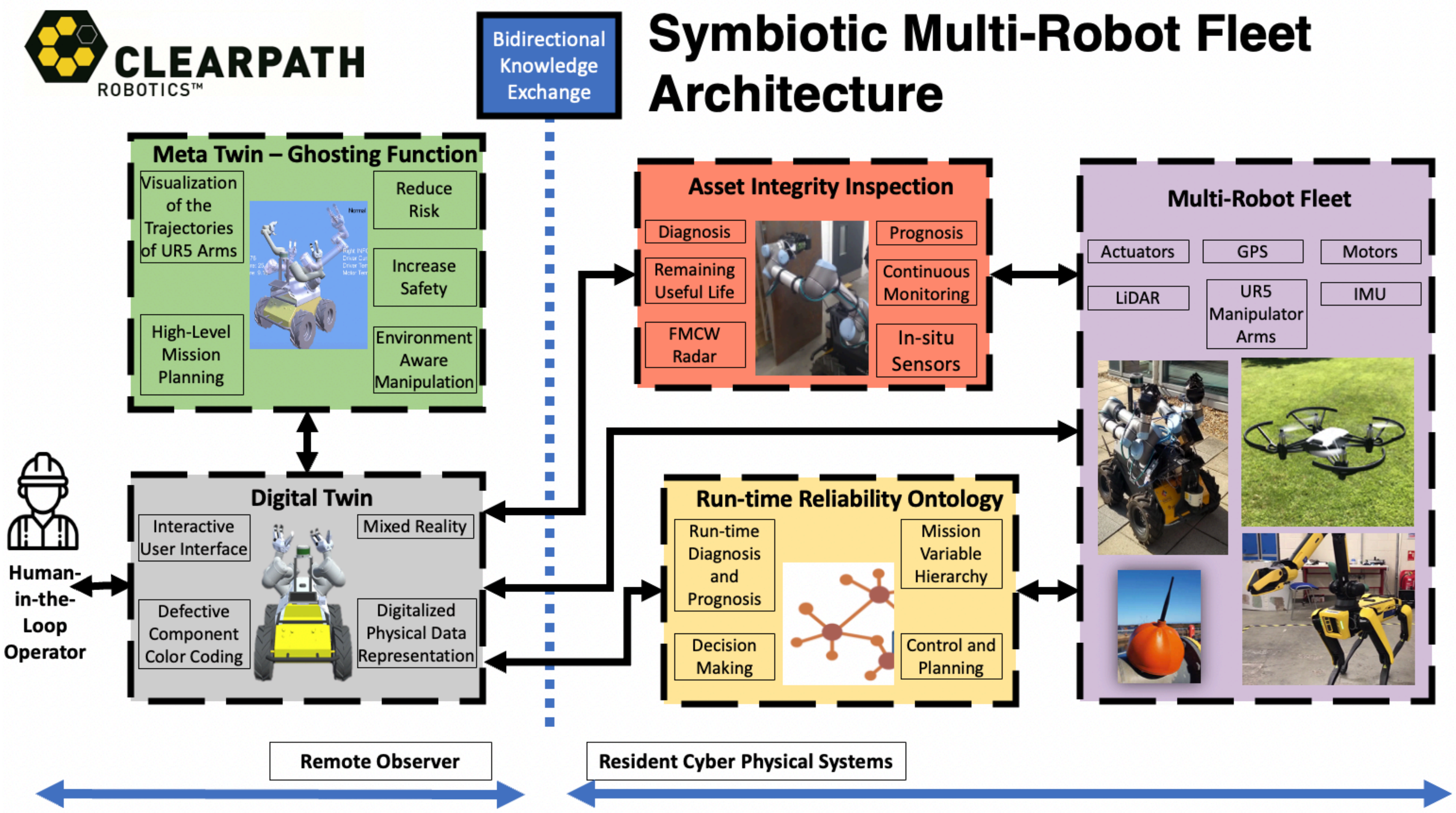


Figure 7-12 Symbiotic Digital Architecture expanded from Figure 7-1 for a Multi-Robot fleet displaying the scalability [10]†.

7.2.3. Deployment of a SMuRF via a Operational Decision Support Interface

The key novelty of this research includes the advantages of a SMuRF where a team of robots leverage the capability of each other when conducting their missions. This work aims to advance resilience, reliability, safety and human-robot partnerships via a cyber physical systems approach within the SMuRF. The solution includes the creation of a ODSI positioned within a digital twin that can synchronously transceiver data and communications across several devices (robot, sensors and systems) to support the exchange of information within a cyber physical system.

7.2.3.1. ODSI interface

An overview of the ODSI and cyber physical architecture is displayed within Figure 7-13 highlighting different features within the interface lettered from A-J. The aim of the ODSI was to allow for a human-partnership across distributed systems enabling for the orchestration and hyper enabled overview of the SMuRF which is deployed BVLOS in the mission environment. This allows for a HITL to utilise information, tools and the robots whilst being remote to the systems in a safe environment. Unity 2020.3.11f1 was utilised to create the interface due to the cross-platform support which is available and as the basic interface could be easily adapted due to the functionality within Unity [369]§.

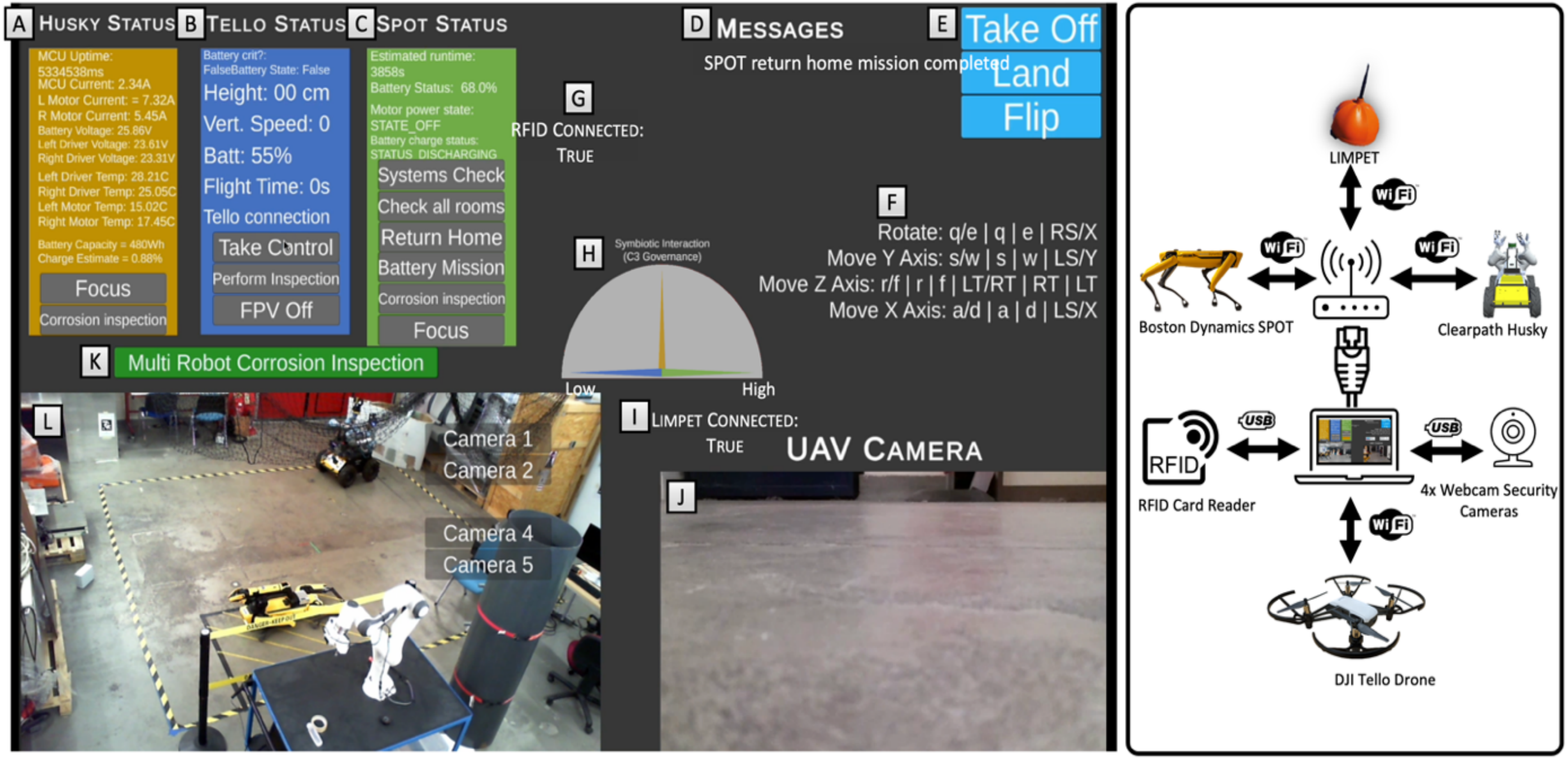
Within the implementation of the ODSI in connecting with the distributed SMuRF, the ODSI is connected directly via ethernet to a WIFI router as displayed in Figure 7-13-right image. The router is implemented to bridge the gaps between the ODSI and the laptops running the scripts for the mobile robots in the SMuRF (SPOT and Husky robots). For the surveillance within the environment three USB webcams are positioned within the infrastructure and connected to two USB hubs via USB extension cables. The USB hubs were to overcome USB-based limitations in connecting more than two webcams to the system on the MacBook connected. As displayed within ‘L’, the webcams can be toggled to view the different video feeds [369]§.

The ODSI is decribed via the labels below for Figure 7-13 and Figure 7-14:

A. Husky Status – Real-time diagnostic data displayed from the Husky and hosts a focus button and corrosion inspection button to initiate a autonomous missions.
B. Tello Status –Tello diagnostics data displayed alongside a take control (teleoperate) button for the UAV. The perform inspection button starts an autonomous mission on

the drone. The First-Person View (FPV) button displays the video from the drone camera to the ODSI.

C. SPOT Status – Run-time diagnostic data displayed and hosts a range of buttons ‘systems check’, ‘check all rooms’, ‘return home’, ‘battery mission’ and ‘corrosion inspection’. This initiates different autonomous missions.
D. Messages area – Imperative key messages for the human operator for safety, resilience and reliability issues or general mission updates.
E. DJI Tello drone buttons – Three buttons including built-in functions on the DJI Tello drone:
    1. Take Off – The motors of the drone turn on ascends and hovers at a set altitude.
    2. Land – The drone automatically descends to land and then the motors switch off.
    3. Flip – The drone completes a backflip and returns to the same altitude.
F. DJI Tello Drone Instructions – Displays the instructions for teleoperation of the drone via the connected input, e.g., keyboard, Xbox controller.
G. RFID Status – A security card feature to ensure authentication of any personnel using the ODSI.
H. Symbiotic Interaction Speedometer – Displaying the levels of C^3 governance where the coloured needles match the status boxes as in A-C for Husky, SPOT and Tello.
I. Limpet – A message area where if a predetermined threshold was exceeded for the Limpet sensor, then a warning would be presented to the HITL related to the environment.
J. The FPV camera on the DJI Tello drone and can be toggled on and off within the Tello status box as discussed in B.
K. Multi-Robot Corrosion Inspection –Simultaneous initiation of the multi-robot inspection mission for the Husky, Tello and SPOT.
L. Security Cameras – Video feed from the security cameras positioned around the environment. Each camera can be toggled via the buttons on the display.
M. Ghosting Function Left – The left sliders control a simulation of the left manipulator on the Husky robot represented in Q (moving the translucent arm).
N. Ghosting Function Right – The right sliders control a simulation of the right manipulator on the Husky robot represented in Q (moving the translucent arm).
O. Send arm trajectory button within Focus – Committing the arm trajectories to the real-world Husky robot and includes an exit button to return to the main segment of the ODSI.
P. Additional Message Box – Displays errors which may occur for arm trajectories proposed.
Q. The proposed trajectories of the arms are displayed in a translucent colour which represents the ghosting function.
R. Husky Diagnostic data - Diagnostic data is fed into the Husky focus interface which is the same data presented within A.
S. SPOT Diagnostic data - Diagnostic data is fed into the SPOT focus interface which is the same data presented within C.



MCU Uptime: 5334538ms
MCU Current: 2.34A
L Motor Current: = 7.32A
R Motor Current: 5.45A
Battery Voltage: 25.86V
Left Driver Voltage: 23.61V
Right Driver Voltage: 23.31V
Left Driver Temp: 28.21C
Right Driver Temp: 25.05C
Left Motor Temp: 15.02C
Right Motor Temp: 17.45C
Battery Capacity = 480Wh
Charge Estimate = 0.88%

Battery crit?: FalseBattery State: False
Height: 00 cm
Vert. Speed: 0
Batt: 55%
Flight Time: 0s
Tello connection

Estimated runtime: 3858s
Battery Status: 68.0%
Motor power state: STATE_OFF
Battery charge status: STATUS_DISCHARGING

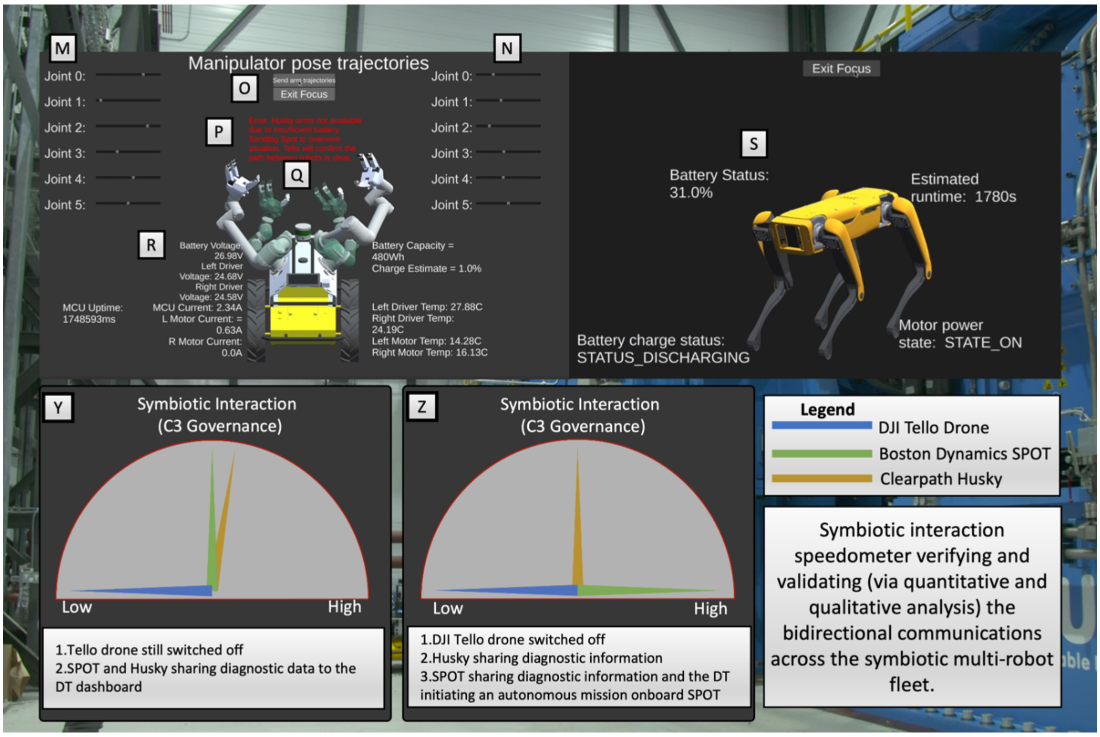
SPOT return home mission completed

RFID CONNECTED: TRUE

Rotate: q/e | q | e | RS/X
Move Y Axis: s/w | s | w | LS/Y
Move Z Axis: r/f | r | f | LT/RT | RT | LT
Move X Axis: a/d | a | d | LS/X

LIMPET CONNECTED: TRUE

Figure 7-13 The ODSI and SDA with the SMuRF positioned in the cyber physical architecture [368,369]†§.



Joint 0:
Joint 1:
Joint 2:
Joint 3:
Joint 4:
Joint 5:

Error: Husky arms not available due to insufficient battery. Sending Spot to overview situation. Tello will confirm the path between robots is clear.

Joint 0:
Joint 1:
Joint 2:
Joint 3:
Joint 4:
Joint 5:

MCU Uptime: 1748593ms
Battery Voltage: 26.98V
Left Driver Voltage: 24.68V
Right Driver Voltage: 24.58V
MCU Current: 2.34A
L Motor Current: = 0.63A
R Motor Current: 0.0A

Battery Capacity = 480Wh
Charge Estimate = 1.0%

Left Driver Temp: 27.88C
Right Driver Temp: 24.19C
Left Motor Temp: 14.28C
Right Motor Temp: 16.13C

Battery Status: 31.0%
Estimated runtime: 1780s
Battery charge status: STATUS_DISCHARGING
Motor power state: STATE_ON

1.Tello drone still switched off
2.SPOT and Husky sharing diagnostic data to the DT dashboard

1.DJI Tello drone switched off
2.Husky sharing diagnostic information
3.SPOT sharing diagnostic information and the DT initiating an autonomous mission onboard SPOT

Legend

🟦	DJI Tello Drone
🟩	Boston Dynamics SPOT
🟧	Clearpath Husky

Symbiotic interaction speedometer verifying and validating (via quantitative and qualitative analysis) the bidirectional communications across the symbiotic multi-robot fleet.

Figure 7-14 Husky and SPOT robot focus features within the ODSI [369]§.

7.2.3.2. DJI Tello Unmanned Aerial Vehicle

Whilst the DJI tello drone was designed to be an educational drone for beginners to practise, having a lightweight and compact drone in your inventory within a SMuRF approach is very useful. This allows for rapid access to inaccessible areas at height alongside the HITL to gain increased overviews of a situation via teleoperation. A limitation within the UAV deployed included the requirement for a direct WIFI connection for operation with the laptop as displayed in Figure 7-13 hence why the router was connected via ethernet to the laptop.

An outstanding GitHub project named TelloForUnity was cloned and adapted to suit the requirements of the ODSI framework [370]. Data such as diagnostics, altitude, battery state, battery percentage, flight duration, speed and connection status was received from the Tello and displayed within the ODSI Tello Status box (Figure 7-13B). The framework for communication of the Tello includes a datagram protocol socket connection that utilises data strings being sent between Tello and server [369]§.

The Tello functions within the ODSI include the following:

- *Take Control*- Teleoperation of the Tello via Xbox controller or keys on a laptop.
- *Perform Inspection*- This button executes a script for an autonomous flight where the drone flies to an altitude of 3m, waits and then descends to land. Replicating the potential for a more advanced drone to execute an autonomous inspection mission.

- *FPV On/Off*- Displays the toggle for the Tello first person view camera onboard the UAV.

7.2.3.3. Boston Dynamics SPOT Robot with Manipulator

The key objectives when integrating the SPOT robot with the ODSI was to access and visualise diagnostic information from the robot alongside the ability to coordinate predetermined autonomous missions for the robot to conduct.

The 'unitybridge' script creates a connection for the ODSI to connect to the SPOT robot and establishes the bidirectional communications. This creates synchronous communications across the two elements via two TCP sockets. The script would access a 'output.txt' file which on specified lines within the file contained diagnostic information. This data can be viewed in Figure 7-14R and S for SPOT and Husky respectively and included battery percentage, estimated duration charge status and power state for the SPOT robot. An overview of the focus function can be viewed from this video overview [365]†.

The 'output' file includes a combination of two scripts. A Python script named 'robot_state_test' collects the state of the robot ad saves this in a specified folder as a text file. This also uses the 'robot_state_client' function from the Boston Dynamics Software Development Kit to access the robot state. The data is then written to the output file.

The inclusion of autonomous missions for the robotic platforms within the SMuRF has a couple of initial benefits. Firstly, teleoperation of the robots is not necessary, therefore the bandwidth of communications can be spared and the robots can feedback information incrementally allowing for smoother data communications which don't get backed up. Secondly, this reduces cognitive load on the HITL as the human does not need to constantly oversee the robot and can trust that the robot will conduct the mission appropriately.

For the offshore sector, wireless communications are limited therefore all data transmit should be limited. Therefore, when a button was pressed within the SPOT Status box Figure 7-13C. For the integration of predetermined autonomous missions, a single letter was transit to the robot such as 'A'. When the robot completes the autonomous mission the letter 'A' is sent back to the ODSI to update on mission completion. A number of autonomous missions were created including:

A. Systems Check- Robot stands on legs, moves the manipulator in a circular motion and sits down.
B. Navigate through all Rooms- The following of fiducials through a corridor to the main demonstration area.
C. Return to Layby- The quadruped robot returns to a layby zone.
D. MR-Fleet Inspection Mission- The SMuRF is deployed to conduct a team inspection to inspect two corroded sheets and demonstrate an asset integrity inspection.
E. Battery Mission- SPOT executes a mission within the SMuRF using its onboard fisheye cameras to identify and collect a battery analogue, and then move to the Husky robot and drop the battery nearby the Husky.

Within the systems check mission this included a button within the ODSI with the aim to check all functions are operating as intended via a short automated mission. The dashboard commands the robot to stand, move the manipulator arm and legs (jogging on the spot) and lie down. The 'unitybridge' receives the letter to initiate the mission ('a') and transmits a letter back to the ODSI to enable the HITL to know the mission was sent successfully. The script calls the mobility of the arm command via the SPOT SDK enabling the SPOT manipulator arm to draw a circle of 1 meter diagram whilst moving the legs of the quadruped. The number 2 is then transmit from the SPOT robot to action mission completed at the ODSI.

For bullet points B and C above the robot executes a predetermined autonomous mission with assigned end goals where the robot utilises fiducials which are fixed in positions in the environment. This enables for the autowalk feature to be deployed where the robot localises itself relative to a previously teleoperated mission when learning where fiducials are in the environment. Fiducials are images similar to QR codes which the robot can clearly identify in the mission environment. SPOT requires for a single fiducial to be clearly displayed in view when conducting the mission for optimum navigation.

Return to layby was a feature created as a safety feature where the SPOT robot could *fail gracefully.* For the offshore sector, this would be effective when the robot is operating in a confined space, identifies a failure, but stopping the mission would mean the robot is difficult to recover. Therefore if the robot can identify the failure, navigate out the confined space and then fail in a assigned layby zone, this would increase the efficiency when recovering the robot.

The SMuRF Corrosion Inspection consisted of the Husky, DJI Tello and SPOT robot all having separate inspection missions simultaneously initiated at the dashboard. Focussing on the SPOT robot, the robot stands up from the layby, walks to the first corroded metal sheet, moves to the second metal sheet and then returns to the layby as displayed in Appendix 13-7.

The battery mission consisted of a symbiotic interaction where a Dual UR5 Husky robot is positioned in the field with a battery fault. The robot requires another battery from the garage area to rectify the status of the robots mission. This is where the SPOT robot can assist via a symbiotic interaction. For this to occur, two models were required to be created for optimal recognition of the objects. TensorFlow was used and was trained on a Ubuntu 18.04 laptop with a NVIDIA GTX 1060 3GB grahics card and 16GB of RAM. 1100 photographs were collected for the battery pack and 940 images were used for the Husky robot from the fisheye lens on the SPOT robot (viewed in Appendix 13-3). The images were then pre-processed and labelled [371]. For both pre-trained models transfer learning was used to train them where a SSD ResNet50 V1 FPN 640 x 640 was used to learn to detect the battery and Husky robot [372]. The training models reached less than a training loss of 0.03 after 20,000 epochs of training for detection of the items.

Within the implementation of SPOT in using these models SPOT firstly searches the battery pack and identifies where it is located. Within the autonomous mission evaluation, an electrical enclosure was utilised as a representative battery. Once the battery is identified with greater than 60% confidence by the model as displayed in Appendix 13-4, SPOT autonomously prepares the motion for getting into position and reaching for the enclosure. Once successful grasping has completed the SPOT robot searches for the Husky robot as displayed in Appendix 13-5. Once the Husky is detected with higher than 60% confidence the SPOT plans the motion to the robot and positions the enclosure one metre away from the robot (route displayed in Appendix 13-8).

7.2.3.4. Dual UR5 Husky Robot

The Husky robot was integrated with the ODSI with a similar methodology as in ‘unitybridge’ which lists diagnostic information including:

1. Machine Controller Unit (MCU) uptime
2. Left and right motor current draw for the MCU
3. Left and right motor voltage draw for the MCU

4. Motor and driver temperature
5. Battery capacity
6. Battery Charge

The ‘unitybridge’ script was designed to interact between the TCP socket in the ODSI and the ROS on the robot enabling for the transmission and receival of commands and sending telemetry information. Two buttons were created in the ODSI and included:

SMuRF Corrosion Inspection (Figure 7-13A)- The Husky conducts a waypoint mission to move to the corroded sheet and then towards the decommissioned wind turbine blade for an asset integrity inspection with the route displayed in green within Appendix 13-7.

Send Arm Trajectories (Figure 7-14O)- This command sends the trajectories of the ghosted manipulators to the real-world robot. However, the laptop connected to the Husky robot returns a battery failure back to the ODSI. This induces the symbiotic interaction for the SPOT robot to proceed with the battery mission and Tello UAV to perform an overview of the interaction between the robots.

7.2.3.5. Limpet and RFID Integration

The Limpet and RFID reader were connected to the PC hosting the ODSI dashboard using a USB cable where a serial port between the devices enabled for communications. The data was read from the serial port where the strong was output to the ODSI. The string was then manipulated via a logic check to provide interactivity with the ODSI. For example, for the accelerometer onboard the Limpet, when it exceeded 2G on any axis, an acceleration event was recorded. This data was recorded at a rate of 2Hz as set by the Limpet internal chip. For the RFID reader, when the correct card is used for access the ODSI will show a successful login and enable teleoperation of the drone.

7.2.4. Results and Discussion

Key results include the advancement of deployable CPS via a SMuRF under the key themes of productivity, safety, reliability and resilience. A future trend of resident robots exists in industry where robots will operate, charge and live in the environments they monitor. Therefore, the ODSI is especially important for robots operating BVLOS as feedback is more difficult to collect and oversee without additional measures in place. There is also advancements in terms of enabling facility operators to operate a range of robots for IMR which may include different brands, types, service operators and operating systems. For example, a pair of robots where one uses ROS and another uses a proprietary system.

To confirm the robustness of the ODSI, a connectivity examination was employed to demonstrate that the foundational data transmission structure has the capability to interact seamlessly and achieve synchronisation with a maximum of 1800 sensors and actuators. This capacity is contingent on the specific platform and computational resources, as indicated in Table 7-4 [331]§. This process validates the reliability of the framework and its adaptability to diverse applications, establishing it as both expansible and universally applicable.

7.2.4.1. Symbiotic Interactions

Symbiotic interactions are inspired from nature and were previously introduced in Chapter 5 where the implementation of this in robotics includes the capability for a system to request information, assistance or support allowing for autonomous missions to be further optimised beyond its current capability. A SMuRF enables this to be achieved via predetermined missions which can be requested at the ODSI depending on the requirement levels of the mission. Within a SMuRF monitoring of symbiotic interactions is important to ensure the robots are actively connected to the ODSI where data and decisions can be shared across the systems.

A symbiotic dashboard speedometer was implemented within the ODSI to measure the symbiosis occurring across the SMuRF during the mission. At the start of the mission and whilst the robots are operating individually, the speedometer reads 0 degrees. When diagnostic information from SPOT and Huskt is relayed to the ODSI, the needle increases due to continuous sharing of data from each robotic platform as viewed within Mitchell *et al.* [365]† and Figure 7-14 Y and Z. At Z within Figure 7-14, the SPOT needle is higher as

Table 7-4 Data transmission framework performance for different computing platforms [331]§.

Platform	**CPU**	**Memory**	**Accepted sensors and actuators**
Desktop PC	2 X Intel XEON (octa-core) @ 2.1GHz	64 GB	> 1800
MacBook Pro 2017	Intel Core i7 (quad-core) @ 2.9GHz	16 GB	850
Jetson TX 2	ARM Cortex-A57 (quad-core) @ 2GHz + NVIDIA Denver2 (dual-core) @ 2GHz	8 GB	500

the SPOT robot had its autonomous mission initiated therefore it would be higher in the dashboard for that short moment.

The rate of change of the speedomemter is presented by equation (7-7). Should communication be received by the ODS interface from any of the robotic platforms within the SMuRF system, the needle undergoes augmentation, capping at 180 degrees. Conversely, in the absence of data transmission for a duration of 16 milliseconds, the needle decreases.

$$S^{+} = S^{+} + (T_x + R_x - Z_0) \tag{7-7}$$

Where,

S^{+} represents symbiotic interactions $0 \leq S^{+} \leq 180°$.
T_x represents transmit data from the ODSI to the robot.
R_x represents received data at the ODSI from the robot.
Z_0 represents 0.1, which slowly reduces the speedometer when no signals are sent between robot and ODSI.

Numerous instances arise during the mission wherein symbiotic interactions occur, as outlined in the following points:

- SMuRF diagnostic information fed to the ODSI.
- SPOT autonomous mission buttons- Transmission and activation from the ODSI dashboard to the SPOT robot to complete autonomous missions.
- Corrosion Inspection Buttons- Activation of autonomous missions for each robotic platform representing human-robot teams.
- Multi-robot corrosion inspection- Activation of predetermined autonomous missions simultaneously across the SMuRF. The symbiotic interaction speedometer increases as all robots work together via C^3 governance to complete the mission.
- Battery Retrieval Mission- As presented in the graph in Figure 7-15, the Husky faces an unforeseen battery fault, where SPOT is automatically deployed by the Husky to rectify the issue. The SPOT retrieves a battery analogue from the stores area and transports it to Husky. Future opportunities for these types of interactions include risk mitigation, safety compliance, improved operational strategy, increases in productivity and resilience.

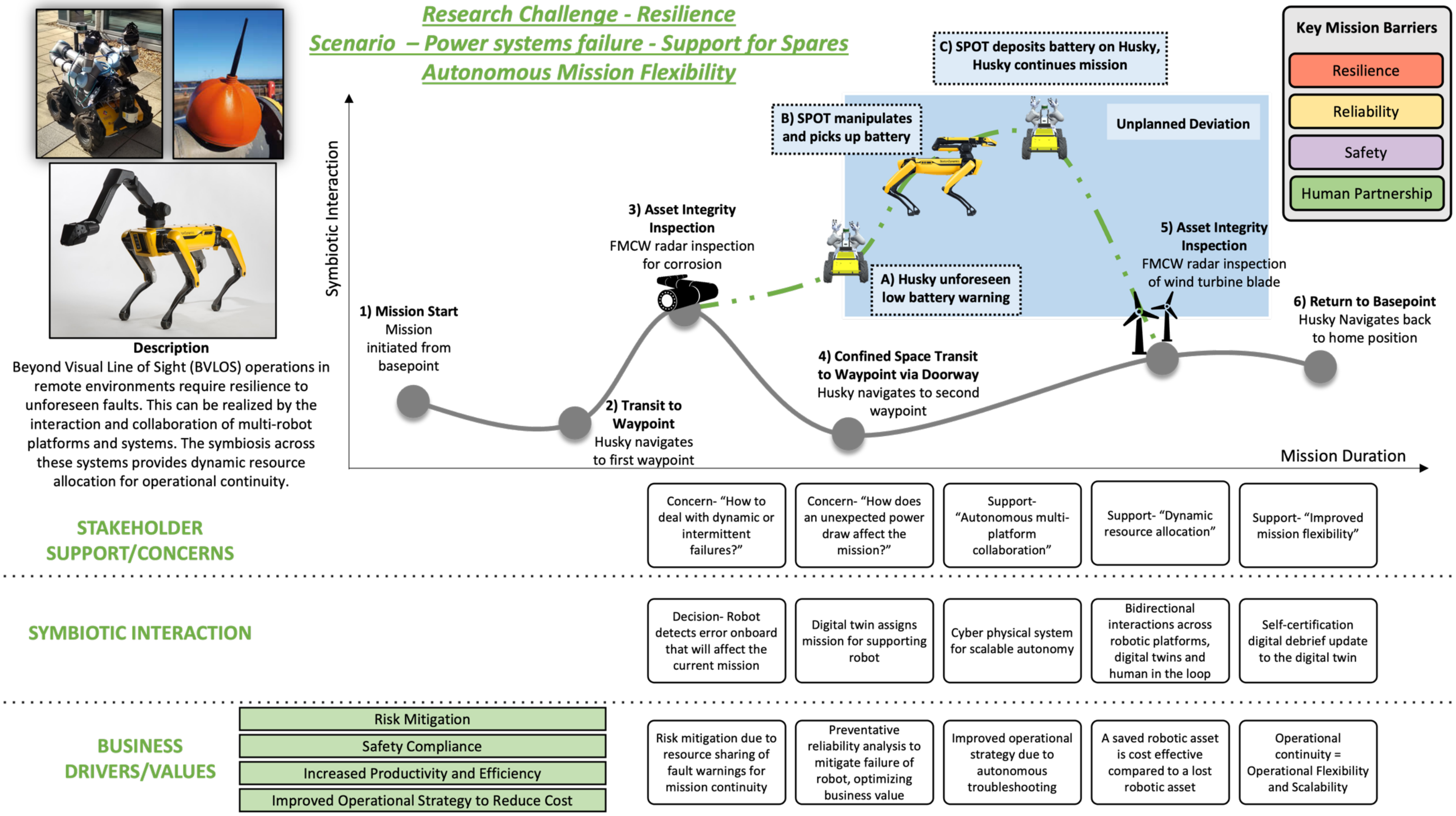


Figure 7-15 The autonomous mission evaluation scenario presented to the cyber physical system.

7.2.4.2. Productivity

Productivity can be quite an ambiguous term with difficulties in quantifying levels of productivity when compared to key performance indicators however, is generally defined as the relation between output and inputs [373,374]. In robotics, productivity is assessed by the ratio of active work time to uptime. Enhanced productivity emerges from individual robots in an MR-fleet executing multiple tasks concurrently. In contrast to a solitary robotic platform, a MR-fleet enables the accomplishment of a greater number of tasks within a set duration. The analysis of the autonomous mission outlined in this chapter involves the depiction of event sequences and the corresponding timeframes for essential objectives achieved by each robot within the autonomous mission envelope, as illustrated in Figure 7-16. Figure 7-16 displays the most optimal autonomous mission where SPOT is the first robot utilised within the mission and the departure from the originally intended mission occurs approximately at 3.5 minutes. Within the comparative analysis of measuring productivity, the departure from the original mission profile is omitted to maintain experimental constants. Therefore analysis of productivity in tasks 1-4 numbered within 7.2.4.1 are presented in Figure 7-16. Productivity (P) is gauged within equation (7-8) [375]. Typically, Productivity (P) is gauged within equation (7-8) [375].

$$P = \frac{Output}{Input} \tag{7-8}$$

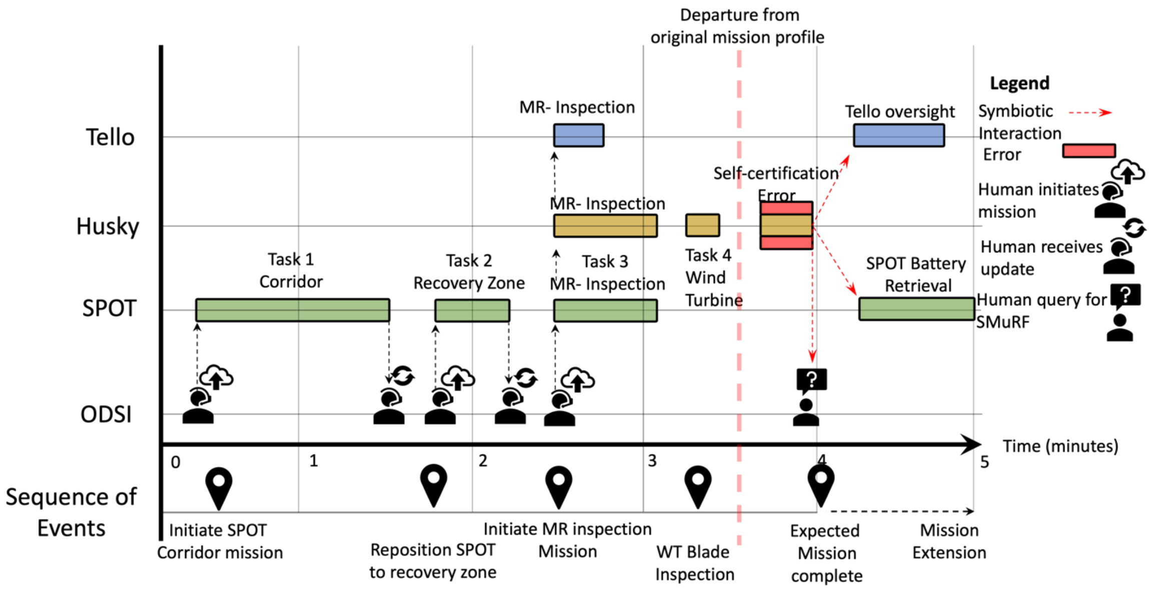


Figure 7-16 Sequence of events during the SMuRF optimised autonomous mission alongside a departure of original mission events due to resilience challenges.

The key measurement within the autonomous mission evaluation includes the duration of the mission and completed tasks. Table 7-5 displays the major event durations whether the aim was to maximise the productivity of the SMuRF as calculated within equations (7-9) to (7-11). The productivity values were calculated by exploring the deployment of robots with different roles to achieve the baseline mission (Up to the dashed red line in Figure 7-16 where the departure exists). The duration of each scenario is calculated via a Partial Factor Productivity (PFP) value and recorded within P_{FDO1}, P_{FDO2} and P_{FDO3}. The robots within the MR-fleet remained the same, however the orientation of primary roles within the mission envelope varied for each scenario where P_{FDO1} represents the productivity of fleet deployment orientation 1.

The most optimised mission orientation included the SPOT being the primary robot in the MR-fleet with a mission duration of 3:03 as presented in the green row of Table 7-5 and P_{FDO1} in equation (7-9). Within the autonomous mission presented to the SMuRF each robot faces different challenges inhibiting the successful completion of the mission, hence why the other orientation of robots deployed in the SMuRF have reduced productivity values, resulting in a longer mission duration.

For example, as displayed in Table 7-5 FDO2, †, the Husky A200 is too wide to safely enter the doorway where the corridor is, therefore the robot navigates to a secondary route to the waypoint in the nearby environment. The robot in some cases, required the HITL to teleoperate through the doorway as it was too narrow. This added on 30 seconds to the mission decreasing the productivity of the mission.

In a second example as displayed in Table 7-5 FDO3, §, when using the tello drone as the primary robot, the first problem identified is that the Tello does not have the FMCW radar installed therefore it requires the Husky robot to complete the inspection segment of the mission adding on 30 seconds to the mission duration.

Finally, Table 7-5, FDO3, ¶ presents the challenge where Tello requires several points in the mission to charge (via wireless charging) which would extend the mission by up to 2 hours or requiring human intervention to swap battery packs.

$$P_{FDO1} = \frac{3:03}{3:03} = \frac{183}{183} = 1\ PFP \tag{7-9}$$

$$P_{FDO2} = \frac{3:03}{3:58} = \frac{183}{238} = 0.77\ PFP \tag{7-10}$$

$$P_{FDO3} = \frac{3:03}{8:00} = \frac{183}{480} = 0.38\, PFP \tag{7-11}$$

The results verify the improved productivity for when the MR-fleet is optimised with correct allocation of tasks for the autonomous roles aligned with required mission objectives. This validates the orientation of using SPOT, Husky and Tello deployed within the SMuRF where SPOT takes on leading responsibility within the autonomous inspection mission. Additional results include the utilisation of the fleet increasing the likelihood of achieving mission success alongside opportunities for corroboration of results from the inspection with verification across other robots. However, when a MR-fleet is not coordinated properly (where robotics strengths and weaknesses are disregarded such as a wheeled robot overcoming stairs) this can result in an incomplete mission due to reliability and resilience challenges not being fully addressed [369]§.

The results for PFP are compared using the set of equations in (7-12) and (7-13) where $P_{A\%}$ represents the PFP of P_{FDO1} versus P_{FDO2} as a percentage, and $P_{B\%}$ represents the PFP of P_{FDO1} versus P_{FDO3} as a percentage. This enables for comparison to identify the productivity improvements.

This signifies an enhancement in productivity, achieved by orchestrating the robots in an optimal sequence with precise task allocation that effectively showcases each robot's capabilities. This advancement is demonstrated by a 23% boost as shown in equation (7-12), and a remarkable 62% improvement as indicated in equation (7-13). These improvements emphasise the increased productivity attributable to proficient fleet management.

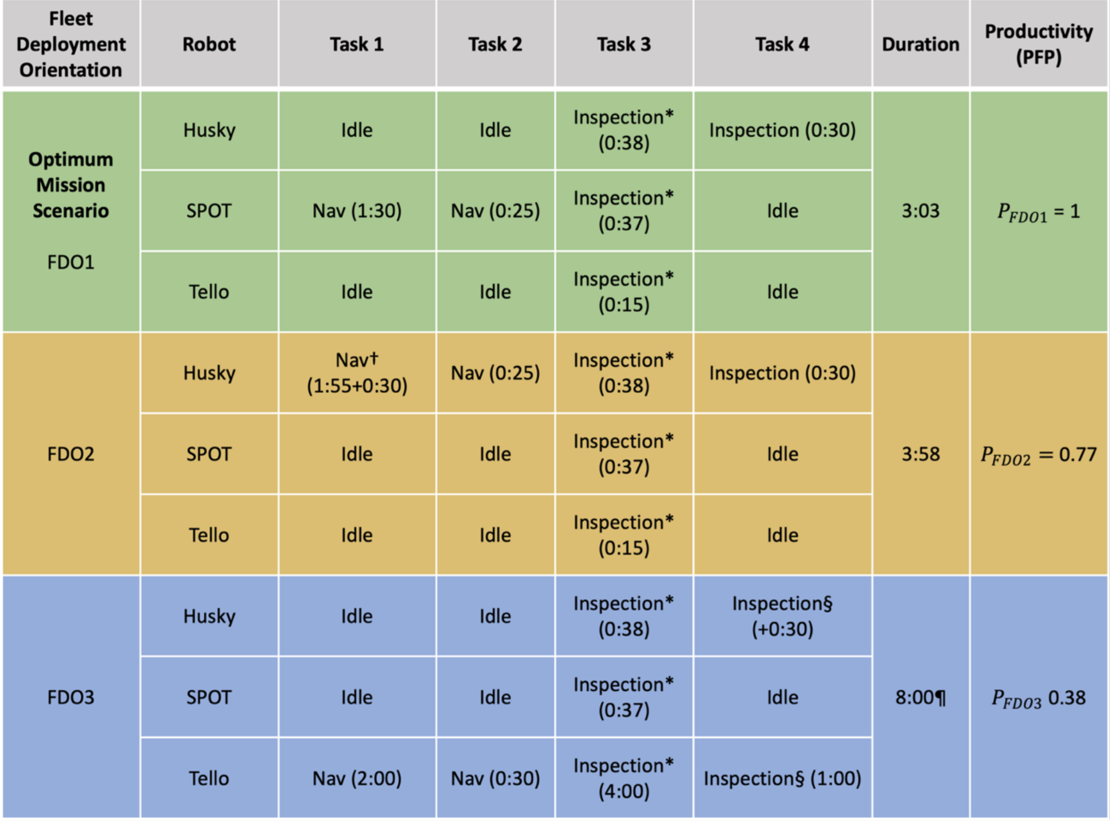
$$P_{A\%} = (P_{FDO1} - P_{FDO2}) * 100 = (1 - 0.77) * 100 = 23\% \tag{7-12}$$

$$P_{B\%} = (P_{FDO1} - P_{FDO3}) * 100 = (1 - 0.38) * 100 = 62\% \tag{7-13}$$

In future, we expect AI will assist humans with fleet management via a co-pilot which makes recommendations for optimised mission profiles and query based learning with the HITL. A similar approach was applied by DARPA where AI piloted a US fighter jet and a pilot operated as a HITL with the aim to have the human pilot focus on wider battle management strategies [376,377].

With respect to robotic fleet management, productivity is linked to the availability and use of resources. For the purpose of this subchapter productivity is defined as the completion of activities and available resources which result in an output to create value for the operator. We expect that the definition of productivity created will expand to include other key performance indicators depending on the facility where a SMuRF is deployed. This may include features such as diagnostics of robots (battery charge expensed), task completion, number of robots to corroborate results, distance covered to improve the productivity values for facility operators. The data from the robots can be used to update mission objectives

Table 7-5 Evaluation of Productivity levels indicating improvements when using the SMuRF approach.
*- Represents when segments of the mission occur at the same time.
†- Husky is a wide load and is unable to fit through single doorways (finds an alternate route +30s)
§-Tello is assigned the mission of Husky however, doesn't have the FMCW sensor installed so can only do visual inspection and needs to request Husky to finish the mission anyway.
¶-longer missions with Tello as primary robot would require charging which can extend missions by up to 2 hours



Fleet Deployment Orientation	Robot	Task 1	Task 2	Task 3	Task 4	Duration	Productivity (PFP)
Optimum Mission Scenario FDO1	Husky	Idle	Idle	Inspection* (0:38)	Inspection (0:30)	3:03	P_{FDO1} = 1
	SPOT	Nav (1:30)	Nav (0:25)	Inspection* (0:37)	Idle		
	Tello	Idle	Idle	Inspection* (0:15)	Idle		
FDO2	Husky	Nav† (1:55+0:30)	Nav (0:25)	Inspection* (0:38)	Inspection (0:30)	3:58	$P_{FDO2} = 0.77$
	SPOT	Idle	Idle	Inspection* (0:37)	Idle		
	Tello	Idle	Idle	Inspection* (0:15)	Idle		
FDO3	Husky	Idle	Idle	Inspection* (0:38)	Inspection§ (+0:30)	8:00¶	P_{FDO3} 0.38
	SPOT	Idle	Idle	Inspection* (0:37)	Idle		
	Tello	Nav (2:00)	Nav (0:30)	Inspection* (4:00)	Inspection§ (1:00)		

alongside watchdog nodes which act ensure self-certification of the autonomous robots. Self-certification is informed by a set of rules from a run-time reliability ontology which was positioned in the cyber segment of the ODSI.

7.2.5. Summary of Findings

In summary, this subchapter presented a SMuRF consisting of a wide range of robotic deployment types alongside several sensors which were also connected to the ODSI featuring bidirectional communications. The ODSI enables for the coordination of the SMuRF froma single laptop in addition to an overview of data, information and camera feed from security cameras to monitor the robots.

This area of research was developed due to challenges and opportunities which exist in offshore wind farm management, reduction of costs, carbon and risks associated with deploying personnel offshore (especially with working at height and in dangerous environments). The concept of the SMuRF originates from the opportunities which exist when robotic capabilities can be leveraged across the mission from a wide range of robots (quadruped, wheeled, aerial and aqueous). For example, a quadruped can access tight stairways, however, cannot reach high areas. This is when a aerial vehicle can assist in the operations to leverage the capability of the mission via symbiotic interactions. This has been focused on the key themes of improving safety, productivity, resilience and reliability of autonomous missions. Within this integration of the SMuRF and ODSI, there are some limitations which are discussed:

A. The capability to rapidly ‘plug and play’ new robots rapidly to the ODSI.
B. Pre-mission simulations of autonomous missions (navigation of robots with LiDAR point cloud) to be conducted in the digital twin ahead of applying them in the real world.
C. The robots to conduct onboard processing to plan and initiate a mission.
D. Orientation of objectives live during the mission.

For the autonomous mission evaluation presented in this chapter, an analogue substation environment was utilised to act as a representative of a substation where robots could be stress tested to fail safely when monitoring the key themes. Industry such as Total, Petronas, British Petroleum and Equinor are currently focussing on ground-up improvements of individual robots conducting IMR operations to address challenges which are current in the industry. Whilst this is important, top-down advancements will unlock the scalability of robots as these companies begin to scale up the deployment of robotics. This is where resilience, reliability and safety becomes crucial so that robots do not become an operational burden to humans deploying them in the offshore environment.

7.3. Symbiotic Autonomous Robot Ecosystem for the Post-Operational Cleanout in the Nuclear Sector

Post-Operational Clean Out (POCO) is a method that was established to ensure the safe processes throughout a Nuclear facility to support both on site operations and decommissioning [378]. The process was developed as nuclear facilities are required to undergo regular inspection and maintenance to ensure the safe production of energy. The nuclear sector in particular undergoes stringent decommissioning protocols due to the importance in safe handlining of nuclear materials [379]. The aims and objectives of POCO include ensuring a safety via reduction of general risks and hazards, minimising chemotoxic and radiological constraints and facilitation of safe demolition and decommissioning of facilities [9,380]†.

To reduce the requirement for humans to be deployed in hazardous environments, RAS are being deployed to gain an improved understanding of nuclear facilities whilst also increasing the safety of personnel who conduct POCO operations [381]. In a similar scenario as the ORE sector, the benefits of mobile robots also apply for the nuclear sector where service robots can access confined spaces, perform inspections and clean-up activities, all whilst a human remains a safe distance from radiation [333,382–385]§.

For RAS, nuclear facilities present themselves with several challenges including unstructured high consequence environments which feature hazards such as chemicals, radioactivity, thermal and other risks which are not visible to the eye. *Defence in depth* is the priority for the nuclear sector, therefore current procedures that take place are well planned and have high precision where often operations which involve humans are substandard, resulting in a loss of critical plant knowledge, extended project timelines which lead to additional costs [386,387]. Heterogeneous robot fleets are a research topic which can leverage the unique capabilities of individual robots as a team to improve inspection capabilities for robots in the nuclear sector. Albeit, the next generation of nuclear reactors are being designed with robots in mind, robots must have the ability to overcome the challenges in legacy nuclear facilities including poor accessibility, wireless shielding due to lead shielding, areas of contamination and radiological activity [9,388]†.

A multi-robot fleet, when compared to a single robotic platform operating in the nuclear sector, offers significant benefits that have not been fully harnessed. To provide context, robots will mainly be used for inspection to measure dose rates of radiation around facilities [389,390]. Firstly, as previously discussed, a MR-fleet enables for a range of capabilities to be leveraged across the inspection mission for radiation. This can allow for more accurate inspections at height, in confined spaces and over the unstructured environment (stairs, obstacles). This also enables for a wide range of sensing payloads to be deployed onboard different robots where missions can be conducted repeatedly with precision. Secondly, whilst robots are able to access radioactive areas, they are still susceptible to failure due to the damaging effects of ionising radiation. Whilst research is being conducted in radiation-hardened/radiation-tolerant robots [391–393], there is further research required to ensure a mobile robot can withstand radiation whilst still being agile and being able to complete tasks required. Thirdly, with the outcome of the previous point, if a autonomous system fails in a hazardous area (due to radiation or general failure) then that would mean that the robot is in most cases unrecoverable. This would mean that valuable sensing mechanisms are lost in the field. This presents more advantages from a MR-fleet as robots can be used to potentially recover a stranded robot and also as sensing mechanisms can be spread across the fleet meaning for a reduction in downtime of operations [394–396].

This section presents a representative non-active nuclear scenario where a heterogeneous MR-fleet is deployed via a digital twin enabling the coordination of the robots via a HITL operator. The cyber physical systems is evaluated within a multi-staged IMR mission within an analogue nuclear environment at the RAICO1 facility, Cumbria, UK. The facility is a testbed that replicated challenges and obstacles within Sellafield Ltd Nuclear facitlity which is currently within its decommissioning phase Ltd. [397]. A Symbiotic Multi-Robot Fleet is presented consisting of the following robots each with their own designated objectivs : Agile X Scout 2.0 and Mini, Boston Dynamics SPOT with manipulator arm, Clearpath Jackal (CARMA) [321], Emika Franka robotic manipulator and DJI Tello drone. An overview of the SMuRF deployed within the analogue nuclear facility can be viewed via a video [398]†.

7.3.1. Methodology

UK regulation requires nuclear operators to conduct POCO every 3-6 months to conduct characterisation of a radioactive facility for asset health monitoring and radioactivity levels. This approach utilised a digital twin to oversee the changes of the environment where the robotic team can also be visualised too. A novel sensing method was also deployed within the investigation alongside a proven radiation sensor to assess for aqueous radioactive contamination which could be detected during the mission [399]§. The system of systems approach via CPS, DT, robots and sensors enabled for information to be attained by the robotic fleet and reported to the HITL to increase their situational awareness at the DT. The approach enables for collected data to be effectively processed, interrogated and visualised with the potential to retain critical historical plant information. Within the evaluation of the system, data was fed back to the DT after the mission for visualisation and processing due to wireless communication constraints within the RAICO1 facility at the time of the investigation [9]†.

A symbiotic system of systems approach is the underlying methodology presented in this subsection extending beyond classic swarming [400], MR-fleet operations [401,402] and differs to DARPA Subterranean Challenge [403], who's teams represent the state-of-the-art to date. This work explores a new extension beyond the state-of-the-art due to symbiosis that takes place across the deployed SMuRF [10,369]§. These findings have been presented in the literature review as discussed in Chapter 4 as a comparison to identify similarities, differences and advantages from the approach discussed in this thesis. For the nuclear sector, new learning must be incrementally integrated to be certain that any new approach decreases risk, maintains/increases safety with a secure pathway. Symbiosis is a necessary and vital step for the optimisation of single robot deployments seeking to scale up within a large industrial landscape. However, the deployment of more robots faces risks which mustn't lead to additional operational hazards [9]†.

The symbiotic digital architecture encompassed by the SMuRF can be viewed within Figure 7-17A where the approach utilises cyber systems and real-world systems to make up the cyber physical system. The human operator has the responsibility of making a series of decisions in the order to coordinate the MR-fleet for a POCO mission. These decisions can be summarised as decisions for locomotion, sensing and perception as displayed in Figure 7-17B Locomotion is a term that encompasses the various methods robots use to navigate,

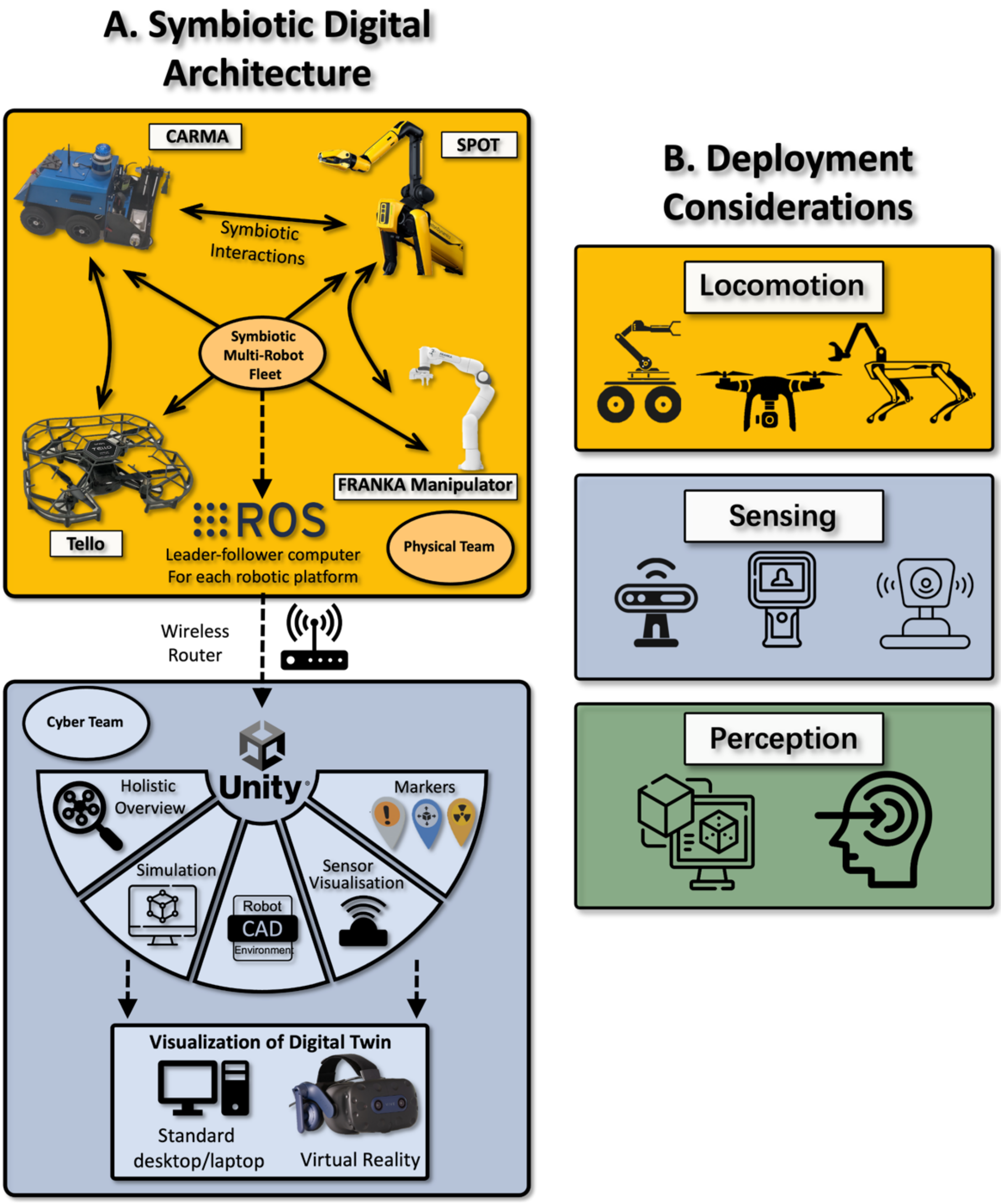


Figure 7-17A. Cyber Physical System and Symbiotic Digital Architecture connecting the links between digital and physical systems. B. Considerations and decisions created when deploying a MR-fleet [9]†.

whether they employ legs, wheels, propellers, or other mobility mechanisms, pertaining to a robot's capability to traverse from one waypoint to another while overcoming terrain obstacles. The collection of sensors or devices onboard a robot is described under sense as different sensors will enable for different inspections and information to be gathered in regard to the environment. Whilst perception typically is used for how robots interpret the environment, we utilise this term to enable how the human interprets (or percieves) the environment from the inspection of MR-fleet. The effective understanding from the SMuRF enables for the design and strategy to implement maintenance procedures and further inspections, focusing back on locomotion and sense for which robot should be next deployed and with which sensors [9]†.

7.3.2. Implementation and Results

The inspection mission using the SMuRF is divided into four segments as displayed in the process diagram in Figure 7-19. Step A involves the 3D mapping mission conducted by the Agile X Scout 2.0 and Mini robots, B includes the teleoperated deployment of the DJI tello drone for imaging areas of interest, C presents the hazard mapping with radiation and FMCW radar sensor to identify aqueous contamination via the CARMA robot and finally a symbiotic interaction is demonstrated via the SPOT, Franka manipulator and CARMA robot to extend the inspection capability. The mission overview and route can be viewed within Figure 7-18 and Figure 7-19 [9]†.

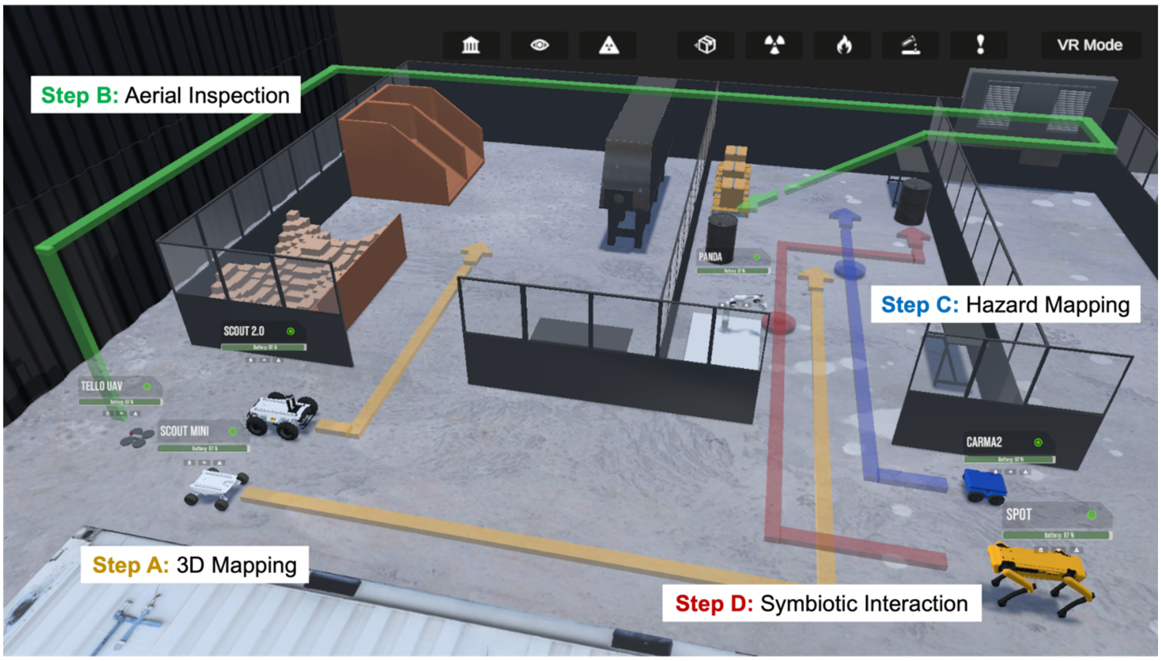


Figure 7-18 The digital twin interface with added markers highlighting steps A-D and routes of the robots during the mission envelope alongside specific waypoints displayed via circles [9]†.

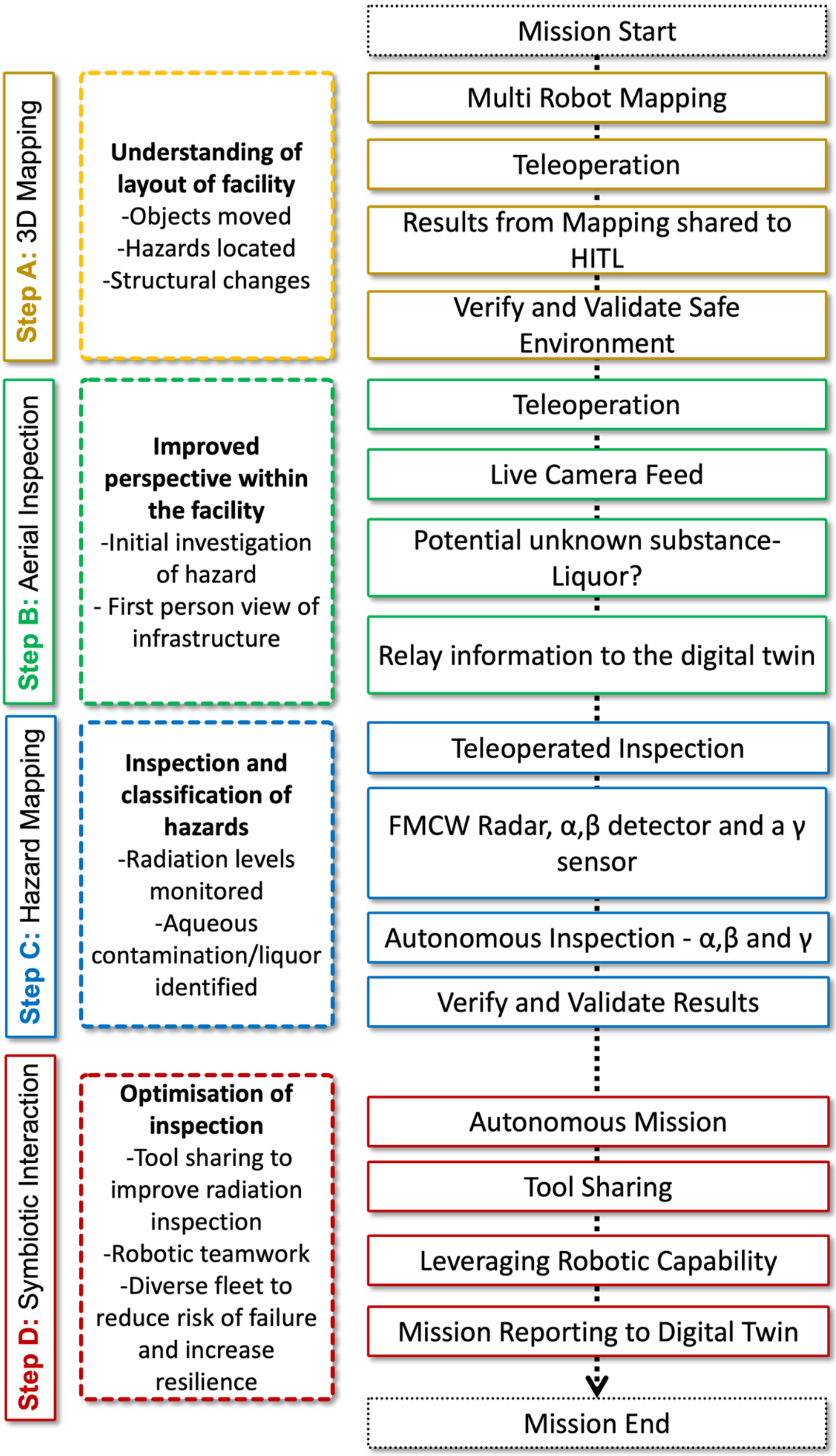


Figure 7-19 Process diagram of the robotic mission envelope with improvements highlighted when deploying a SMuRF alongside a CPS [9]†.

The aim of step A included a 3D mapping task to account for dynamic changes in the environment such as hazards, moved objects or structural changes detected using 3D point cloud data. This information was then overlaid against the Building Information Models (BIM) in the digital twin, which consisted of the previously known layout of the building. The 3D mapping data was collected by the Agile X Scout 2.0 and mini which used a

Velodyne VLP-16 LiDAR (more information about the robots presented previously in section 6.4). This initial step was vital to gain an initial understanding about the state of health of the facility and was prioritised to allow for subsequent tasks to be planned with higher safety. Both robots utilised odometry from the wheel encoders to populate the 3D map accurately which consisted of an occupancy grid allowing for global localisation and navigation throughout the environment. Octomap was used to points are clustered into vertices and then converted into voxels. The implementation of octomap was made easier as it is already configured to operate with a number of robots by incrementally matching 3D scans for each robot [404]. The real-time map, created by combining sensor data from individual robots, was managed and continually updated at the facility's central control center. Here, point cloud messages from multiple robots were processed in a sequential order using a queue, and the voxel data was adjusted accordingly. Figure 7-20AB displays the outcomes of the 3D mapping task superimposed on the facility's inspection area's central control data [9,405]†. It should be noted that for Section 7.3 the data from the run-time mission was not streamed automatically into the digital twin at this stage. The data was

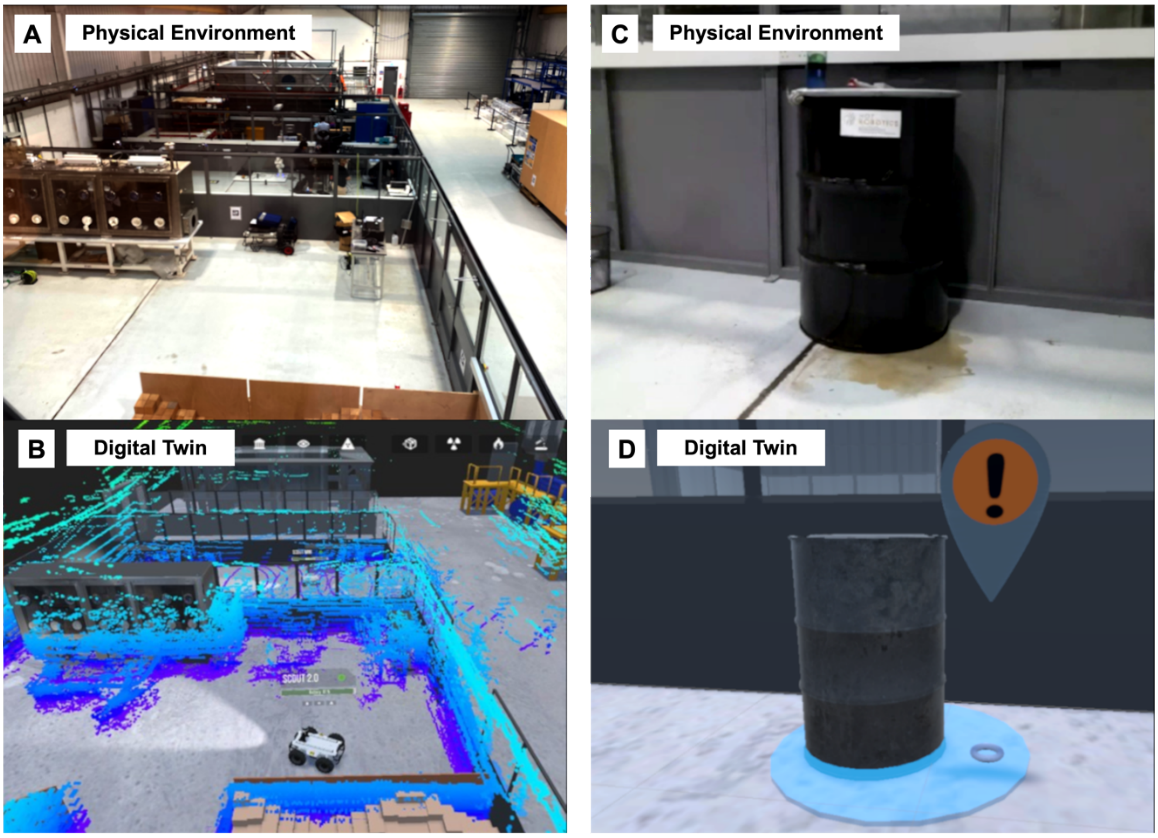


Figure 7-20 AB- Results from step A highlighting the 3D mapping mission of the RAICO1 facility where A displays a photograph of the real environment and B displays the generated voxels overlaid within the existing BIM in the DT interface. CD- Results from the aerial inspection where C displays the real world asset and D presents the digital twin interface with the general caution hazard tag displayed for the human operator [9,405]†§.

processed and then uploaded to the digital twin due to bandwith challenges faced in the facility [9]†.

The CARMA robot was deployed within step C for further investigation of an area with a potential spill that was identified via the UAV camera. The CARMA robot utilised the FMCW radar sensor, α, β detector and a γ sensor [35–37,348,406,407]†§. Via the FMCW Radar, the aim was to validate the area to identify if it was aqueous and via the radiation sensors we could determine which type of radioactivity was potentially present [408–410]. The CARMA robot can be viewed within the inspection mission as in Figure 7-21 where A displays the robot within the digital twin interface, B presents the real robot in the inspection area and C showcases the planned path and area via a user interface at the controller of the robot [9]†.

Stainless steel drums are often used to encapsulate metallic intermediate level waste where a dense material (grout) is utilised to fill the gaps within the material under storage. During inspections conducted by Sellafield Ltd, numerous containers were discovered to display significant deformation, resulting in safety concerns for the plant. The distortions were attributed to the production of gases which were detrimental to the integrity of the barrel containing the materials and could lead to a flammable hazard. In addition, corrosion of the

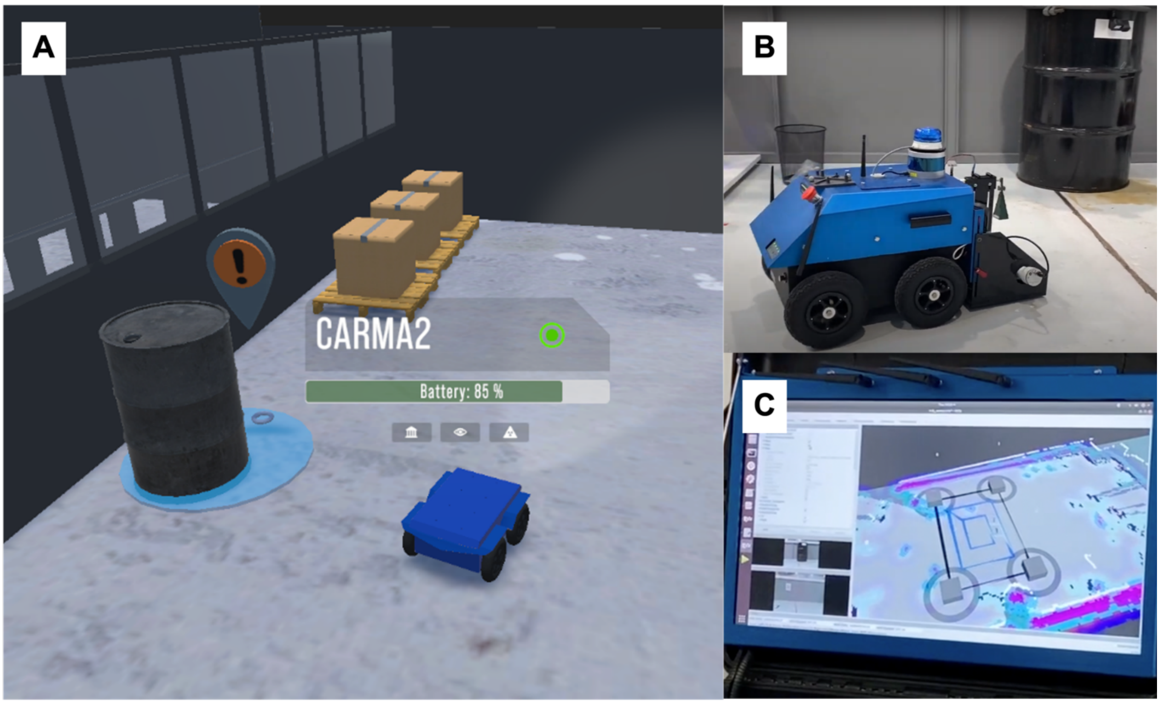


Figure 7-21 A- Digital twin displaying the CARMA in the respective environment, B- The CARMA robot deployed in the real-world environment and C- Generated data from the FMCW radar, Alpha and Gamma sensors [9,405]†§.

barrels could lead to a release in the metallic contamination which can be particularly difficult to clean when it becomes aqueous. Therefore, inspection procedures should be in place to ensure the containment of the radioactive metallic level waste and structural integrity of the barrels [411]. With this information the aim of the CARMA robot was to classify the type of potential leakage around the barrel where three examples include [9]†.

A. A concrete flooring which is dry and therefore safely contained radioactive material
B. A safely contained material where non-radioactive liquid (water) is located on the drum (For example, the liquid does not originate from the drum thereby is not a contaminated radioactive leak).
C. Liquor contamination on the floor which is a recognised radioactive hazard and could promote the corrosion of contacting drums.

For the investigation a solution was created to represent aqueous contamination via Epsom bath salts (Magnesium Sulphate) to represent the radioactive liquor. This choice was made because the presence of salts in the water would elevate conductivity, thereby enhancing the contrast in the solution. This mirrors the conditions in real-world radioactive liquid, where metallic radioactive elements also contribute to increased conductivity. Furthermore, the inclusion of Epsom bath salt induced a noticeable colour shift to dark brown, providing a reliable reference point for the solution's location. This offered significantly improved precision compared to using just water, thereby enhancing the confidence in assessing the spill's localisation. The successful classification of each situation are presented in Figure 7-22. The findings indicate that the liquid solution produces a higher return signal amplitude compared to water and dry concrete flooring, aligning with as expectated. This trend is consistently observed in both the intermediate frequency overview and the detailed interface

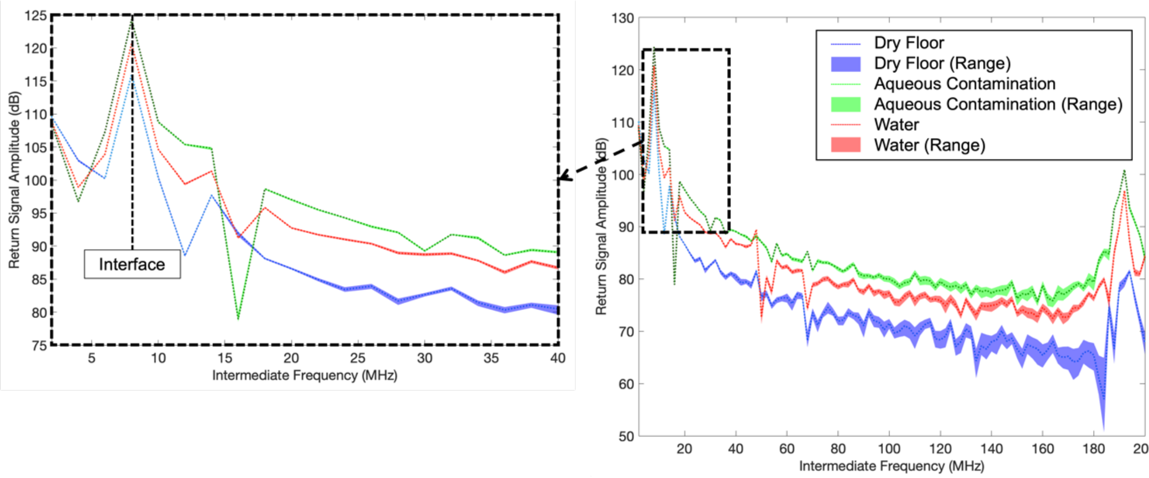


Figure 7-22 Successful detection and classification of liquid liquor solution, water and dry concrete flooring [9]†.

analysis (as shown in the magnified section of Figure 7-22). This research paves the way for enhanced procedures in the event of potential contamination, as distinguishing between aqueous and dry contamination is crucial for determining appropriate cleaning methods during POCO Additionally, failing to detect such contamination could result in a robot spreading the contamination more extensively, as exemplified in the liquid scenario presented in this article when compared to a dry case [9]†.

Upon the completed inspection, the operator then entered the automated waypoint inspection mission for the CARMA robot to complete via the autonomous path planner. The robot then performed an autonomous inspection of the surrounding area recording data from all its sensing modalities in the area surrounding the barrel [9]†.

Step D of the mission included the deployment of a symbiotic interaction between CARMA, Spot and Franka Manipulator arm as significant γ activity was identified at the spill location. The symbiotic interaction can be viewed within Figure 7-23. The deployment of Spot was initiated by the operator at the DT interface. For the first step of locomotion, the Spot robot autonomous navigated to the mobile garage (Figure 7-23A and B), where the Franka manipulator is positioned. The Franka arm was preprogramed to provide the correct tool (γ

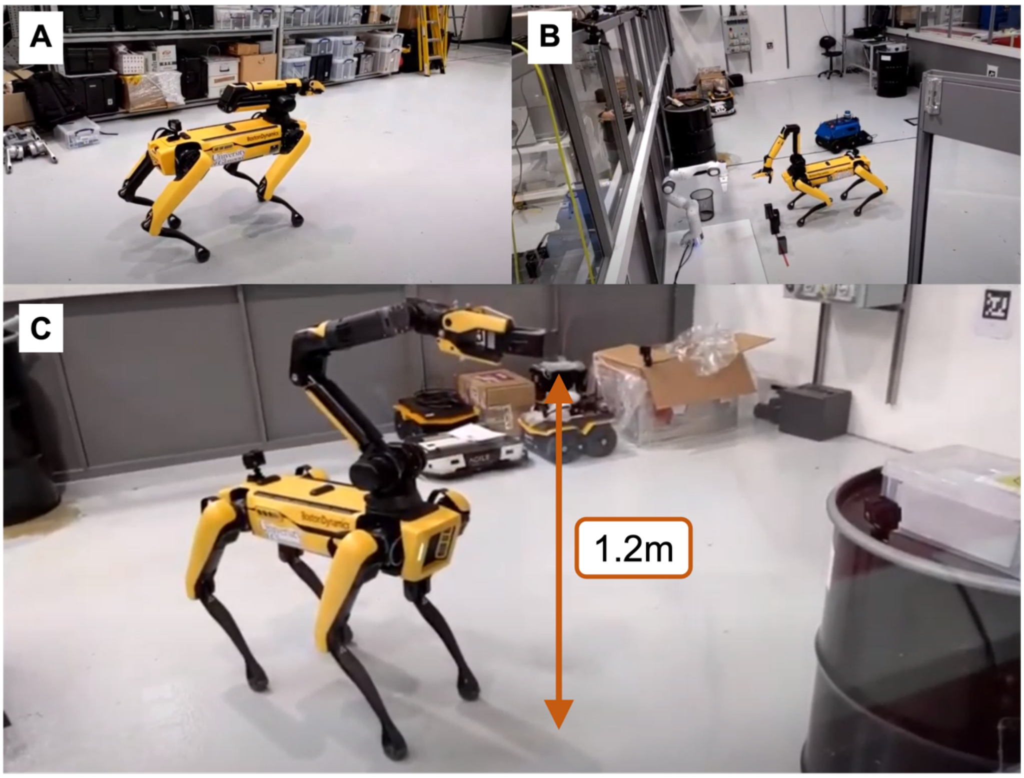


Figure 7-23 Spot and Franka Panda Manipulator exhibiting a symbiotic interaction: (A-C) SPOT traversing the mobile garage and performing a vertical scan of the identified area with the γ sensor [9]†.

Thermo Fisher Radeye G10 sensor) for the Spot robot to complete the remainder of the mission. At this point it is appropriate to remind the reader that the nuclear sector is not necessarily interested in autonomy for all sections of a Nuclear facility. From the interest of the nuclear sector, they are also interested in teleoperation to ensure autonomy does not lead to any failures. Hence why the next segment of the mission required the deployment of a human to teleoperate the robotic platform [9]†.

The human operator teleoperated the Spot robot via the controller to grasp the sensor, the robot was then navigated to the area to conduct the inspection where the scan ranged from ground level to approximately 1.2m high (Figure 7-23C) with discrete interval scans of every 0.055 metres. These heights were corroborated with a Vicon unit positioned around the surrounding environment however, in future we would expect Spot to calculate these heights by itself. Once the vertical scan was completed, the robot was then teleoperated back to the mobile garage to return the sensor and then back to the home position [9]†.

The resulting vertical scan generated an array of gamma dosage values (in arbitrary units) and corresponding heights (in meters), can then be visualised in the DT interface. Figure 7-24 illustrates this visualisation concept, where 3D disc objects are created. The size and colour of these discs are mapped based on the dosage readings, accompanied by a radiation hazard tag for easier identification of the identified hazard [9]†.

To implement this concept in Unity3D, we translated a range of simulated recorded gamma dosages into 10 levels, ranging from 1 (lowest) to 10 (highest). Each level was assigned specific size and colour parameters. For the lowest dosage level '1', the disc had a size value of 1.0 in the Unity3D x,z scale and featured a light blue colour material, corresponding to the initial point of the colour scheme. On the other hand, for the highest dosage level '10,' the disc was sized at 2.0 and coloured in dark red. These discs were then stacked vertically, ranging from ground level to the maximum height where the gamma sensor could scan [9]†.

It's important to note that the sensor readings were simulated (using arbitrary units) due to safety constraints. This precaution was taken to ensure the safety of personnel working in the RAICO1 facility, as using real γ radiation can be hazardous. The robotic arm moved upward in stepped increments, which is why the simulation results in Figure 7-24 are presented in a similar fashion to reflect this movement. For more information on detecting γ radiation, you can refer to sources [412,413].

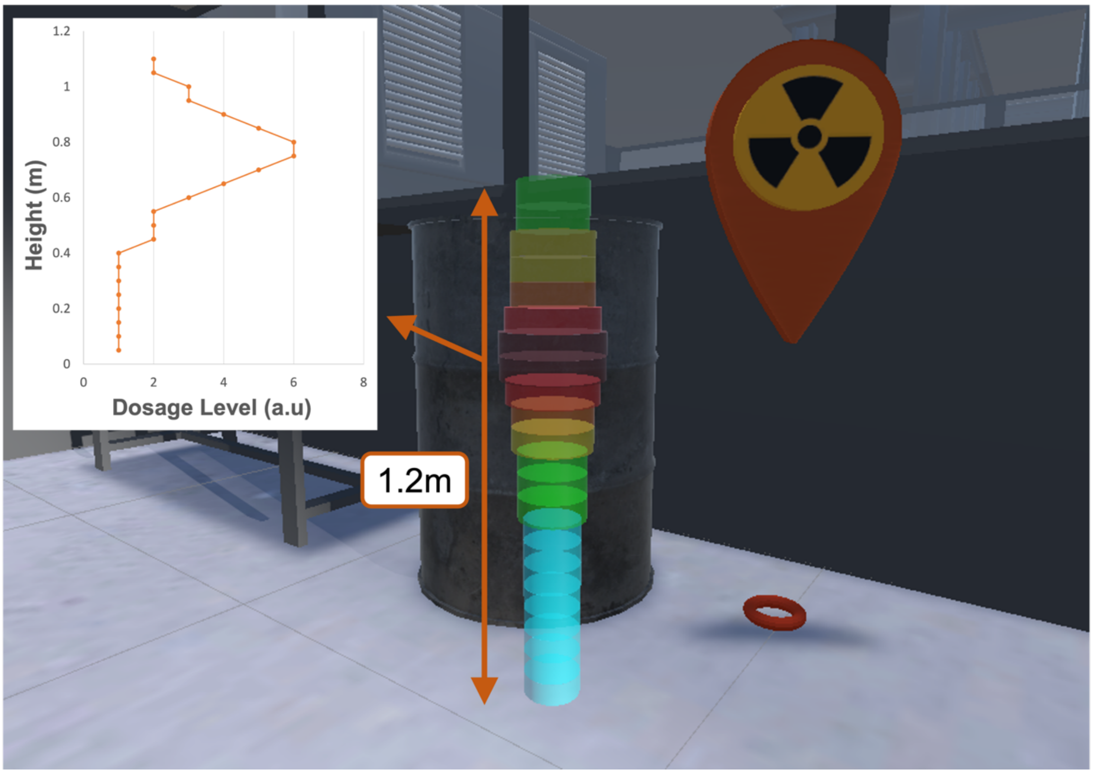


Figure 7-24 Digital twin interface highlighting the readings from the z-axis scan for gamma radiation [9]†.

In summary, this section has reported on the methodology and implementation of a semi-autonomous inspection mission using a symbiotic multi-robot fleet via a cyber physical system. The cyber physical system consisted of many types of robotics and sensors including camera, LiDAR, FMCW, alpha and gamma radiation, where information was fed into a single digital twin environment which allowed for robotic operators and inspectors to view and tag areas of concern from the inspection mission of the robots. This allowed for increased safety of humans where information from the fleet can be used to inform on future decisions for POCO for dynamic and extreme environments [9]†.

7.3.3. Discussion

This section presented the first implementation of a robotic fleet (cyber physical system approach) within the RAICo1 mock-up nuclear facility which was setup to simulate a decommissioning POCO scenario and presented to Sellafield Ltd. The SMuRF was deployed with the intention to inspect an area for asset health monitoring and radiation levels [9]†.

Significant insights have been gained through the preparation process for deploying a MR fleet and the strategic decisions involved in coordinating these robots for POCO missions.

At present, there is a noticeable absence of established procedures or regulations guiding MR-fleet deployment. Consequently, this research is poised to provide a framework for the effective utilisation of robots in nuclear facilities [9]†.

In our approach, we contemplated the information that an engineer would already possess about the inspected facility, such as floorplan blueprints. We also considered the information they would need post-inspection. For instance, the initial assessment prioritises identifying noteworthy environmental changes within the facility. This preliminary evaluation serves as the basis for creating a task list that guides subsequent inspection, maintenance, and repair activities. The following subsections delve into the key findings and lessons derived from this endeavor [9]†.

7.3.3.1. Symbiotic Interactions

Symbiotic interactions across the SMuRF enabled for an improved inspection volume when compared to if a single robot was to conduct the mission. Whilst the CARMA robots primary design function is to measure levels of radiation on the flooring for α, β and γ radiation, limitations are faced due to the robot not having an manipulator arm to measure these same radioactivity measurements at height. Whilst it may seem intuitive to deploy a similar robot which is larger and with a manipulator arm this is not always the case. This can lead to timely downtime of operations and an expensive robotic platform in addition to the new robot having complications in areas such as confined spaces or other ATEX compliance issues. This is why it is useful to have a MR-fleet as the other robot does not have to have all of the capabilities of the CARMA robot, just the ability to share some of the responsibility. This is why symbiotic interactions are advantageous as the SPOT robot is very agile and has a built-in manipulator, therefore it could share a sensing capability with the CARMA robot and conduct the extension of the mission. Gaining the information of sensing for radiation at different heights is useful as from a dosimetry context, measuring does rates at multiple heights is useful to determine the risks associated with the environment.

A scenario was presented to the team to discuss why a single robot with a wide range of sensors onboard was not considered appropriate. The main reason for this was in a potential detrimental scenario where a robot becomes unrecoverable or stranded. This could be due to navigational issues in resilience when overcoming unstructured environments or due to damage from harmful radiation which can destruct electronics. In addition, if a single robot has all of the sensors onboard, then once that robot becomes stranded then operations must halt to a standstill if there are not more of the same sensors readily available. In the scenario where one of the robots from a SMuRF fails there are still benefits for the facility operator and for the humans who deployed the robotic team. Firstly, progress can still continue in the inspection of the facility which benefits the manager of the facility as there are several robots in operation in the MR-fleet. Secondly, for the humans who deployed the robot team, one of the robots in their fleet can be used to oversee the failed robot to help to diagnose the issue of the robot. Thirdly, a suitable robot in the fleet may be used to help recover the damaged/failed robot to a safe area to enable for human retrieval of the robot. In summary, symbiotic interactions allow for adaptive mission profiles where when challenges are faced, the diverse capabilities across the MR-fleet can be used to overcome these issues [9]†.

A second symbiotic interaction also took place within the facility. Whilst this interaction was not automated, it was implemented via the HITL who identified a potential solution and deployed the correct robots to detect and diagnose the problem to properly validate the issue. The DJI tello drone was deployed via a teleoperated flight around the environment where a dark puddle was identified from the Tello cameras. In considering this flight, it would have not been efficient to fly a larger drone within the facility with the FMCW Radar deployed onboard as this would limit the drone to be unable to fly in confined spaces due to this being an indoor flight. However, this is why symbiotic interactions are mutualistic. Whilst the DJI tello can fly in confined spaces, the CARMA robot can then be designated to the identified area to conduct the required mission by the Tello. In summary, this segment of the mission demonstrated the extended capability of a mission via symbiotic interactions where a group of robots could complement each other by rapidly adapting to the environmental or inspection requirements which may dynamically adapt throughout a mission. In addition, this allowed the HITL go gain increased situational awareness about the mission to reduce risks and take the appropriate intervention to maintain the integrity of the infrastructure [9]†.

7.3.3.2. Digital Twins

The digital twin in this scenario improved the situational awareness and visualisation of the facility. This significantly reduced the need for human exposure in what could be a radioactive area. The digital twin lead to improved mission planning and provided an interface where operators could make critical interventions through informed decision making from 3D data, exploration and perception. Within this segment of work, the DARPA

SubT challenge was identified as the state-of-the-art as presented in Chapter 4.2. Therefore, we aimed to address elements of minimising cognitive overload via the use of our digital twin and a hazard tags feature. Operator cognitive overload was effectively minimised by incorporating hazard tags corresponding to the environment. This approach allows the HITL to oversee the mission and seamlessly transition into the virtual representation of the facility to pinpoint hazard tags. Consequently, this reduces the time pressures faced by the HITL responsible for monitoring the fleet's operation, which is guided by a task list. Furthermore, the digital twin enhances trust by providing a comprehensive view of the environment and the status of the inspection mission. Additionally, the digital twin interface includes a direct robot teleoperation feature, which holds particular significance in the nuclear industry. This functionality is vital for situations where autonomous operation is not desirable for critical tasks.

Preserving he continuous exchange of data was a key segment of the cyber physical systems approach whether it be with commands of teleoperating the robots or the recording and visualisation of data in near to real time. However, it was also important to store and replay previous mission scenarios via the DT interface. Offline reviews of previous missions provided an excellent use case for the provision of accurate and reliable information during report generation of exploration and routine inspection missions within the nuclear sector. We also implemented a feature that enables users to label hazards, problems, and incidents for future reference. This allows stakeholders to review and stay informed about the team's ongoing activities, ensuring they are kept up to date.

7.3.3.3. Sensing Aqueous Contamination

Acquiring information to distinguish between wet and dry contamination holds great significance for stakeholders in the nuclear sector. For instance, in the case of deploying a Boston Dynamics SPOT robot in Chernobyl's reactor 4, the decision to use a quadruped platform over a wheeled one was driven by the need to minimise the contact surface area when navigating within the facility. This choice aimed to reduce the dispersal and escape of radioactive dust [414]. Conversely, if a wheeled robot such as CARMA were used, driving over contaminated liquids could lead to further spreading and the contamination of the facility with radioactivity [9]†.

Furthermore, the determination of the ground's surface composition is crucial for monitoring radiation levels in the vicinity of a facility and for ensuring the effectiveness of the robotic platform's self-certification [399]§. This is especially important because radiation has the potential to damage the electronics onboard the robotic platform.

While the FMCW radar sensor could have been employed to investigate the physical properties of an active solution, this aspect fell outside the scope of our current work. Exploring alternatives such as oils might have been considered, but the research conducted provided a reasonable and well-justified comparison within the context of nuclear-specific scenarios.

7.3.4. Conclusion

In conclusion, this subchapter reported on the deployment of a SMuRF deployed within a POCO scenario for a analogue nuclear facility with the aim to improve safety and inspection accuracy for a HITL operator. The key metrics of this subchapter identified increased operational awareness within the environment for the remote human operator alongside improved robotic capability within the mission via symbiotic interactions which leverage the capability across the mission profile. In addition, the FMCW radar sensor was deplpoyed to provide a new sensing technique to investigate aqueous contamination to better understand hazards present within POCO [9]†.

Section 7.3 makes significant contributions by focusing on enhancing reliability, ensuring safety compliance, and bolstering resilience in the context of multi-robot missions through symbiotic interactions. It also introduces query-based learning to facilitate human involvement in achieving the ultimate goal of providing symbiotic autonomy as a service. The primary goals outlined in this article encompass the development of a digital twin interface capable of accessing almost real-time data from a multi-robot fleet operating symbiotically, promoting interactions among robots within a team, and introducing an innovative application of microwave radar sensing for inspecting ground integrity to pinpoint potential water contamination within a nuclear facility. A composite image with respect to a SMuRF deployed in a Nuclear facility in the future is displayed within Figure 7-25 to aid in the visualisation infrastructural sensors and robotics interacting in the hazardous environment whilst feeding back information to a HITL at the digital twin [9,415]†.

Figure 7-25 The SMuRF presented within a composite image in a nuclear environment highlighting infrastructural sensors, ground and aerial vehicles positioned together [9,415]†.

8. Non-Destructive Sensing and Foresight Monitoring

Current economic infrastructure is a dense network of systems that provide energy, transport, water, waste management, telecommunications and flood defences that provide vital services. Maintenance of this infrastructure requires periodic inspection to ensure the safety for personnel and safe operation of the asset. For example, the American Road and Transportation Builders Association reported that nearly 231,000 (37%) of US bridges require repair work. In addition, 46,000 were classified as structurally deficient and recommended that 81,000 bridges should be repaired [37]†. In a second example ensuring critical infrastructure, it was expected that between 2020-2021 the UK government would spend £1.5 billion in resurfacing damaged roads by winter conditions. In addition, insufficient salt dispersion during winter in the UK can result in dangerous driving conditions whilst excessive dispersion of salt has adverse environmental effects and wastes precious supplies of salt and funds [406]§. Finally, composite structures have been proven to be cost-effective but also provide challenges in the assessment of their structural integrity. Unfortunately, composites do not provide early signs of failure which can be visualised accurately when compared to metallic equivalents which undergo well-defined corrosive

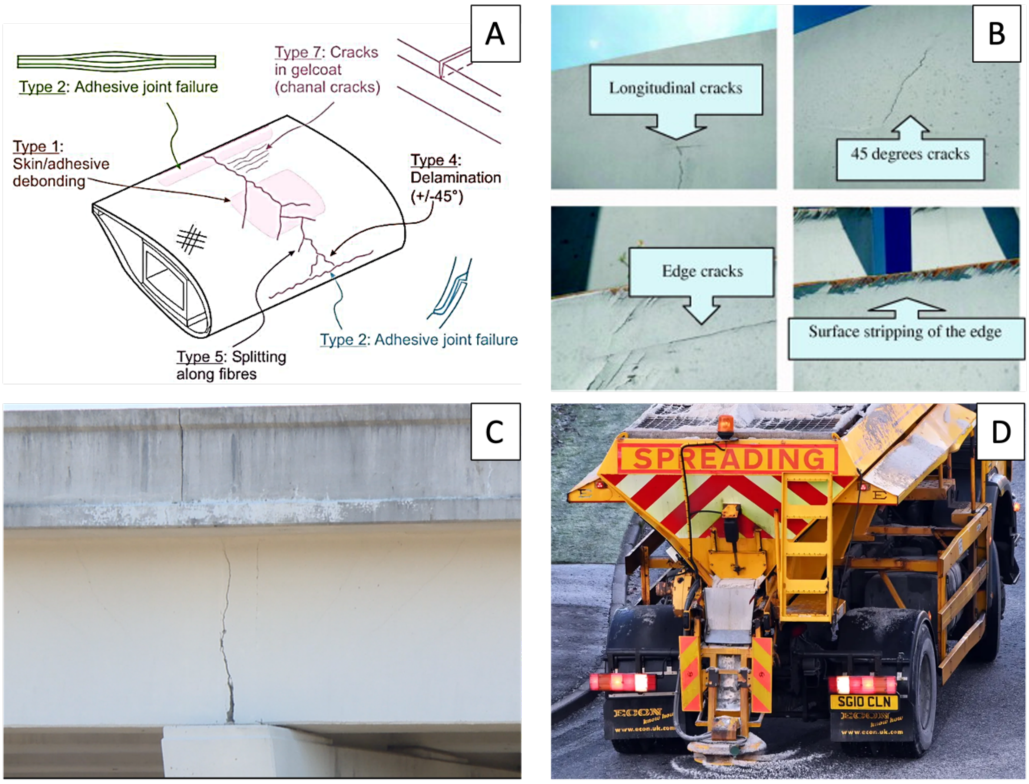


Figure 8-1 A. Diagram of failure mechanisms on a wind turbine blade. B. Images of failure mechanisms on a wind turbine blade. C. Cracking on a bridge in Tennessee, USA. D. Deployment of a UK gritter dispersing salt on roads during winter [487].

routes to a major defect. Whilst wind turbine blades are now made of composite materials, it thereby becomes vital to observe the damage progression to reduce the risk of catastrophic failure and monitor costs of the asset [36]§. Examples of failure mechanisms can be viewed within Figure 8-1 A-C alongside an image of a UK gritter spreading salt in D.

Non-Destructive Evaluation (NDE) is an instrumental sensing mechanism which is in development for asset integrity inspection with the aims to prevent failures to ensure the safe operation of industrial equipment and facilities. The technique allows for fault precursors on assets such as wind turbine blades, civil infrastructure and metals to be detected which are not visible to the eye and lie in the subsurface. The early detection of these faults can lead to reduced downtime of an asset minimising the need for costly repairs or replacements further on in the lifecycle of an asset.

Gupta *et. al* provides an effective overview the background reading of non-destructive sensing technologies of structural composite materials including mechanical vibration-based NDE, Imaging-based NDE and Electromagnetic Spectrum-based NDE alongside a comparison of advantages and limitations of the sensing technologies. This section will focus on the deployment of a novel non-contact sensing method, which uses FMCW radar and has been utilised for several use case deployments for asset integrity inspection and foresight monitoring.

The following chapter provides an evaluation of the patented FMCW Radar sensing for two use cases [416]:

1) Non-Destructive Evaluation for Structural Health Monitoring

Utilising FMCW radar sensing for comprehensive assessment of surface and subsurface properties is proposed for enhancing asset integrity inspection in critical infrastructure. This sensing approach represents an advancement over existing methods, where many sensors are confined to surface measurements or necessitate direct contact with the material under examination. The FMCW radar sensor stands out with its non-contact capability, compactness, and lightweight design, making it suitable for deployment on robotic platforms to conduct inspections from a distance. This innovative approach facilitates accelerated asset inspections, providing engineers with early detection of fault precursors. Consequently, this enables minimal downtime for assets and allows for proactive implementation of maintenance procedures.

2) Foresight Monitoring

This includes using the microwave sensor to provide increased foresight to threats or provide increased operational information enabling for increased situational awareness of visible and non-visible threats. This improves the state-of-the-art when compared to standard visual line of sight sensors and can be used to supplement data collected by LiDAR and cameras for data which is out with the immediate mission space. Foresight monitoring enables a robot to update safety governance protocols ahead of an event occurring leading to increased safety or avoidance of risks. This work aims to improve trust, resilience and safety compliance for robotics and autonomous systems [368]†.

8.1. Frequency Modulated Continuous Wave Radar Theory

The FMCW Radar signal produces a continuous frequency change over time to produce a saw-tooth frequency output which can be viewed in Figure 8-2. The disparity between the frequencies of the transmitted and received signals is established through the convolution of the input and output waves, resulting in a novel Intermediate Frequency (IF) signal of reduced magnitude. Subsequently, this IF signal is scrutinised to derive distance and velocity parameters for objects within the sensor's field of view. The frequency based IF signal is then transmitted to a data logger for analysis Δf. A summary of the IF signal is as follows in equations (8-1) to (8-6):

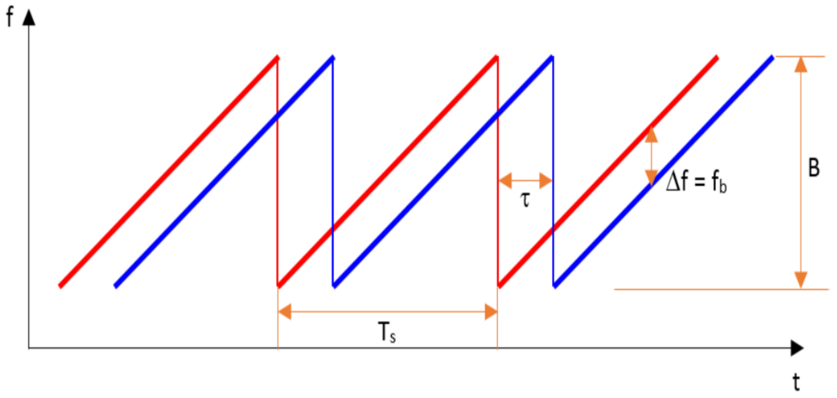


Figure 8-2 Resulting sawtooth from the transmit and received signals from FMCW radar where f = frequency, t = time, Ts = sweep duration, τ = two way travel time of return signal, B = sweep bandwidth and Δf= intermediate frequency [349].

$$f_{RF_{out}} = f_{RF_0} + k_f \times t \tag{8-1}$$

Where $0 \leq t \leq T_s$, the initial frequency is f_{RF_0}, frequency sweep time (chirp duration) is represented by T_s and k_f is the sweep rate.

$$k_f = \frac{B}{T_s} \tag{8-2}$$

Where the frequency sweep bandwidth is B. The two-way travel time of the signal is where $\Delta t = \tau$, of the emitted signal is calculated as:

$$\tau = 2\frac{d}{c} \tag{8-3}$$

d is the distance between the first target (reflecting the signal) and the antenna where c is the speed of light in the medium of propagation.

For all cases we assume that the speed of light in air to be equivalent to the speed in a vacuum. Therefore, the emitter frequency will be equivalent to equation (8-4) due to the observed delay in return signal.

$$f_{RFreceived} = f_{RF0} + k_f * (t - \tau) \tag{8-4}$$

where, $\boldsymbol{\tau} \leq \boldsymbol{t} \leq \mathrm{T_s} + \boldsymbol{\tau}$. The intermediate frequency ($\Delta \boldsymbol{f}$) between the emitted and received signal is therefore:

$$\Delta\mathrm{f} = \mathrm{k}_f * (-\tau) \tag{8-5}$$

The following expression can be used if the negative time of flight (return signal to the transceiver) is taken as a magnitude:

$$\Delta f = \frac{B}{T_s} * 2\frac{d}{c} \tag{8-6}$$

Equation (8-6) requires the distance between the antenna and target interface to be kept constant to effectively evaluate key amplitude responses pertaining to the target properties. This equation means that any variation out with the specified distance would not be attributed to the intrinsic properties of the target or asset integrity of the material and instead attributed to a difference in the distance to the target. For some applications in the field it may be difficult to maintain an accurate distance to the target, therefore to address this challenge it can be possible to create a library of known responses to an 'ideal reflector' for the range of distances from the sensor to the specific target too acquire signal contrasts. The remainder of this subsection presents the antenna characterisation and sensor equipment.

8.1.1. Antenna Characterisation

To generate a radiative output profile for a Flann K-band antenna model (#21240-20/serial: #219405), a Vector Network Analyser (VNA) was configured to produce a K-band signal. The VNA was connected to the antenna via a high-frequency Pasternack coaxial waveguide. Three scans were conducted using a two-dimensional translation stage, coupled with a WR42 type open-ended waveguide standard probe designed for the K-band (18-26.5 GHz). The separation distance between the non-radiative near-field probe and the antenna was maintained at 100 mm during the scans. The data sets were implemented to represent the

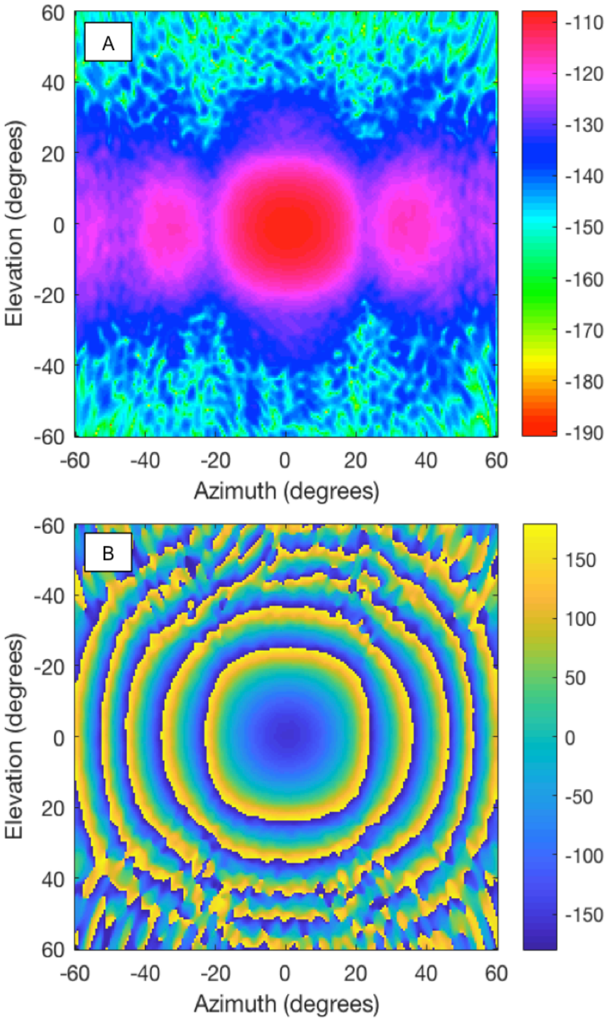


Figure 8-3 A) Two-dimensional amplitude radiation pattern in the K-Band for Flann Microwave antenna model #21240-20 (scale bar in dBm). B) Two-dimensional phase shift radiation pattern in the K-Band for Flann Microwave antenna model #21240-20 (scale bar in degrees) [36]§.

1500MHz bandwidth sweep used for the radar module. The two-dimensional radiation patten acquired by the antenna is presented in Figure 8-3A where Figure 8-3B presents the phase shift characterisations of the Flann antenna with the VNA configuration [36,417]§.

The aim of this characterisation study was to measure the sample area on the target, determined consistently within a radius when all operations were carried out at a fixed sample-antenna distance of 100 mm. The Flann microwave antenna demonstrated a dispersal characteristic in its radiation pattern, with a peak amplitude indicating a spot size on the target of approximately 36.4 mm radius at a separation of 100 mm. This minimal phase differential represents the effective field of view of the sensor [36]§.

8.1.2. FMCW Radar Equipment

A block diagram displaying the workflow of the FMCW Radar methodology which can be distributed as 6 essential segments [348,349,407,418]§:

A. The FMCW radar electronics which creates the sawtooth wave with a 1500MHz bandwidth sweep within a 300-millisecond chirp duration. The data acquisition was set to one reading per second.
B. A Flann standard gain horn antenna rated to 17.6 – 26.7 GHz with a nominal gain of 20DBi at 22.15 GHz. The antenna was either mounted via tripod or positioned onboard the robotic platform. Typically the horn was positioned 10cm from the target interface
C. The material under test can be utilised for asset integrity inspection or foresight monitoring however, each scenario will require the horn antenna (B) to be directed towards the target interface of the material under test.
D. Matlab was utilised to create a graphical user interface for rapid deployment and analysation of the data from the radar sensor.
E. The waveforms of the reference and return signals were convolved to produce an intermediate frequency, as previously presented in equation (8-6).
F. A Fourier transform was utilised in the data processing where amplitude extractions were analysed and presented. These extractions are stored to create a library of material responses for the successful identification of contrasts for different variables.

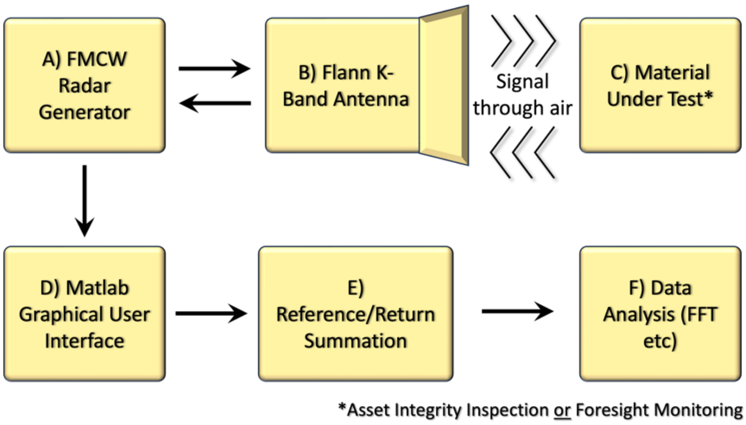


Figure 8-4 Experimental setup displaying hardware and data processing steps alongside flow chart of the analytical procedure where the target interface can be for asset integrity inspection or foresight monitoring [36]§.

Table 8-1 Parameters of the FMCW Radar sensor throughout investigation.

Parameter	**Value**
Band	K – Band (24 – 25.5 GHz)
Chirp Duration	300 milliseconds
Bandwidth	1500 MHz
Acquisition Frequency	1 Hz (0.2 – 3 Hz tunable)

8.2. Dielectric Theory

A continuous sweep in the frequency domain is provided by the FMCW radar sensor which enables for key advantages when compared to a pulsed radar using a single frequency. This includes a improved signal to noise ratio, broader frequency range, decreased intermediate frequency and the ability to operate with less detrimental effects to ambient environmental conditions [418].

The attenuation and dispersion of electromagnetic waves in materials are controlled by dielectric relaxation processes, characterised by the relative permittivity ε_r^*. These processes result in the damping of localised oscillations in constituent materials at varying rates across the component scale range, influenced by the frequency of incident radiation. The observed return signal amplitude in porous materials which are low dielectric is affected by several factors. These include interfacial geometry, surface contaminants, fluid content, type of fluid and volume of high permittivity minerals [419]. Related work in this investigation previously addressed the signal response to oil and water within a geomaterial in the X and K-bands. This capitalised on the significant attenuation due to the significant absorption of the signal by water for both frequency bands. Blanche et al. offers a comprehensive account of the interaction between porous media, partially saturated with fluids, and internal geomaterial properties using non-invasive FMCW measurements [407,418].

8.3. Methodology

The configuration of the FMCW radar, as illustrated in Figure 8-5, facilitated both surface and subsurface analysis of the material under examination as displayed within the key. Data collection from the horn antenna was conducted using Matlab as part of this inspection method [420]§.

The utilisation of the sensor for both static and dynamic investigations required a number of variables to be consistent within the evaluation of the use of the sensor. As previously discussed, the distance from the horn antenna to the sensor was important to ensure the data was consistent as presented in equation (8-6). Due to the sensor having penetrative qualities, for some materials, the senor signal can easily penetrate right through the material to detect walls behind the material (as discussed within foresight monitoring in 8.4.2). Therefore, for asset integrity inspection, it was important to ensure the background area beyond the material under test within the laboratory was clear or remained the same as this could have an effect on the return signal amplitude of the signal. The investigations were often conducted at least three times to ensure successful validation of the results investigated within the experiments. Finally, the cable between the horn antenna and FMCW signal generator was to be kept consistent. Within the preliminary investigation a 30 cm waveguide was used which featured

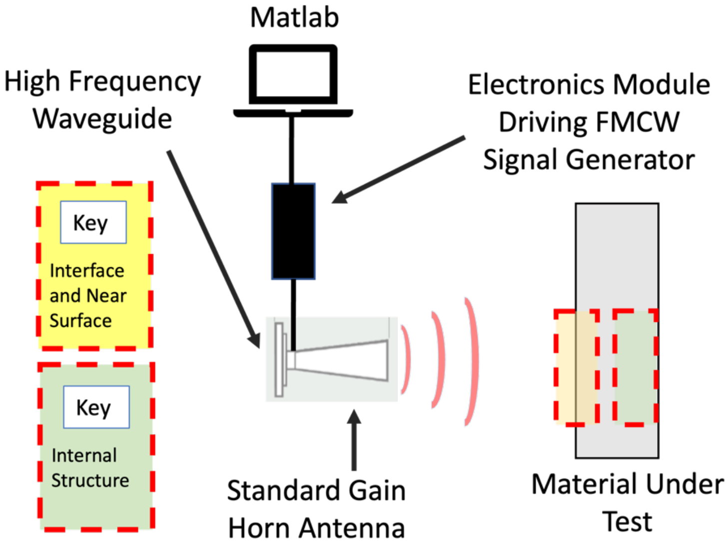


Figure 8-5 General experimental setup with material under test positioned a known distance away with relevant equipment [420]§.

contrasting results for the early return signal analysis. To minimise this risk, a fixed adaptor was used which would mean the distance the signal travels from the generator to the horn antenna remained the same throughout [348,420]§.

8.4. Implementation and Results

The following section presents the evaluation of the microwave sensor for specific use cases where collaborations existed with UK energy utility companies in the inspection of wind turbine blades and overhead line detection. Next the evaluation of the radar for inspection of civil infrastructure is presented for the detection of iron rebar and water ingress within sandstones. Finally, we present foresight monitoring within 8.4.2 for human detection through doorways and for ground integrity inspection.

8.4.1. Non-Destructive Evaluation for Structural Health Monitoring

8.4.1.1. Wind Turbine Blades

The Paris agreement stipulates a 70% reduction in energy rel. ated emissions by 2050 when compared to current levels to limit global warming to 1.5 °C. This has accelerated the growth of renewable energy and in particular offshore wind energy production where in 2020 record growth was seen where 93GW of new capacity was installed in wind power resulting in a 53% year on year increase according to the Global Win Energy Council [421].

In the pursuit of enhancing the efficiency of wind turbine energy capture, there is a trend toward developing longer and wider turbine blades. To achieve this, composite materials including glass fibre-reinforced polymer and, in some instances, carbon fibre-reinforced polymer are increasingly favoured [422]. While composite materials have proven to be cost-effective, the enlargement of blades and the subsequent rise in load levels present challenges in detecting surface and subsurface defects and precursors to failure modes. Various defects, including those induced during manufacturing such as cure-induced, flow-induced, or preform defects, as well as those occurring during operation and maintenance, pose significant challenges. Factors such as moisture, absorption, sleet, ultraviolet irradiation, atmospheric corrosion, fatigue, wind gusts, and lightning strikes can cause damage to the blades. The nature of the reinforcement and the polymer matrix makes it challenging to detect early signs of damage, unlike ductile metallic components that exhibit well-defined elastic and plastic deformation or corrosion pathways [423]. This inherent characteristic results in substantial nontrivial costs in wind turbine blades and presents difficulties in implementing early damage investigation diagnostics and maintenance strategies [35,424]§.

Wind turbine blades are essential for the effective capturing of wind energy to electric energy. Ensuring the integrity of wind turbine blade assets is complex as the structures are exposed to significant dynamic and static forces, gravitational loads and aerodynamic drags over their 20–25-year lifecycles [425]. In addition, they are constructed using several types of materials including epoxy resins, composites and adhesives. Therefore, it is important that they are maintained to provide efficient conversion of energy. Wind turbine blades have incorporated composite materials to enhance their strength, with these enhancements directed towards reducing manufacturing costs and extending the operational lifespan of these assets [36,426]§. A list of common wind turbine blade defects can be viewed within Table 8-2.

The decommissioned wind turbine blade sample is presented within Figure 8-6 displaying a type 4 delamination defect. The aim of the investigation was to identify a contrast in return signal amplitude for a health segment of the wind turbine blade against the dry delamination identified in the right image of Figure 8-6 and when water ingress is positioned within the same delamination. The microwave radar was situated 10cm away from the target interface, with a field of view on the exterior of the blade measuring 4.2 x10^{-3} m^2. This would represent a hidden, subsurface defect which is a current challenge in identifying the integrity of the blade which previously would require contact or invasive procedures of the asset structure; which often requiring damaging healthy areas of the blade to investigate a potential unhealthy area.

Table 8-2 A list of defect types for wind turbine blades [36,488]§.

Type	Description
1	Adhesive layer damage formation and growth in bond joining skin and main spar flanges (skin/adhesive debonding)
2	Adhesive layer damage formation joining the up- and downside skins along leading and trailing edges (adhesive joint failure)
3	Damage formation and growth at the interface between face and core in sandwich panels in skins and main spar web
4	Internal damage formation and growth in laminates in skin and/or main spar flanges, under tensile or compression load
5	Laminate skin and main spar splitting and fracture of separate fibers (fiber failure in tension; laminate failure in compression)
6	Buckling of skin due to damage formation and growth in the skin and main spar bond under compressive load (skin/adhesive debonding induced by buckling, a specific type 1 case)
7	Formation and growth of cracks in the gel-coat; debonding of the gel-coat from the skin (gel-coat cracking and gel-coat/skin debonding)

Figure 8-6 Wind turbine blade sample displaying a type 4 delamination defect and a zoomed in view of the area used to insert water ingress. Note that the internal failure is not visible via line of sight to the horn antenna positioned at the exterior of the blade [36]§.

8.4.1.1.1. Healthy segment versus Damaged Delamination

This segment introduces fundamental tests conducted to evaluate the sensitivity of K-band FMCW radar to variations in the structural integrity of wind turbine blades. Figure 8-7 illustrates the disparity in return signal amplitude between a defect-free wooden core section of a wind turbine blade and a section with a similar wooden core structure and thickness however, featuring type 4 defect damage. At this point it is important to emphasise that the defect is not visible to the horn antenna as the defect occurs internally on the structure of the blade. Therefore, any deviation of signal from the baseline measurement would result in the successful detection of the delamination. These results are presented in Figure 8-7 where the return signal amplitude for the health baseline is higher than the return signal for the decommissioned segment of the blade, indicating successful detection of the type 4 defect. The healthy baseline and data for the delamination defect display a consistent peak at Bin 5 representing the target interface corresponding to a distance of 100mm from the horn antenna. The return signal amplitude of the health segment is 0.47 x10^6 arbitrary units (a.u.), with a type 4 defect giving an RSA of 1.94 x10^5 a.u. at Bin 5. This displays a significant contrast in the signal in the detection of healthy and defective segments of the blade. The contrast is consistent between bin 5-14+ providing valuable information regarding the pore content in a porous composite material and represents the complex interfaces within the structure of the composite [36]§.

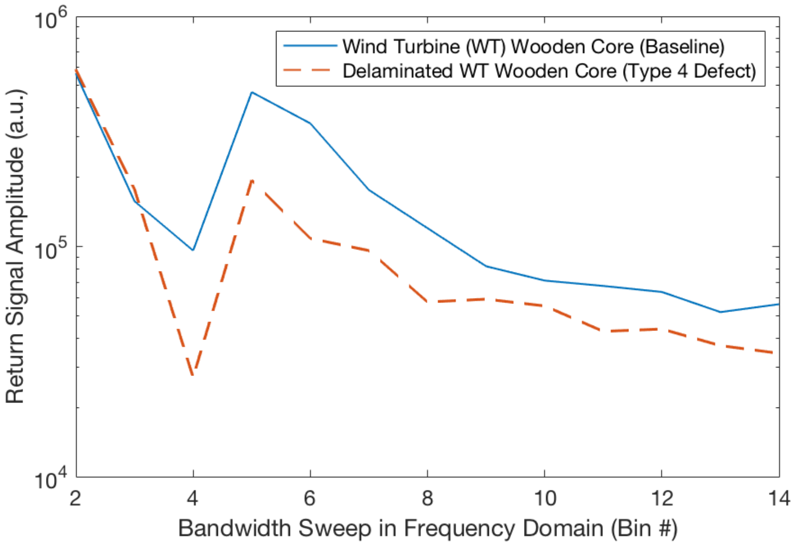


Figure 8-7 Analysis of the return signal amplitude in the frequency domain for the dry delamination defect (type 4 defect) versus the healthy segment of wind turbine blade [36]§.

8.4.1.1.2. Water Ingress within the Delamination Defect

The investigation results are presented in Figure 8-8 for the type 4 delaminated wind turbine blade with water ingress positioned inside. For this data, the return signal amplitude is presented with respect to time to identify the contrast between healthy segment, dry delamination and water ingress within the delamination. The data point collected is Bin 7 which presents the data on the subsurface of the wind turbine blade sample. In summary, the following trend is identified:

1. The Return Signal Amplitude (RSA) for an undamaged baseline area of the turbine blade structure is approximately 1.0×10^5 a.u. - indicative of a low dielectric constant and consistent thickness as expected for a structure composed of porous polymers reinforced by layered carbon fibre and glass resins.

2. In contrast, the RSA for the damaged and delaminated area of the turbine blade structure ranges between 0.65 and 0.7×10^5 a.u. - reflecting a lower dielectric value than the healthy baseline due to increased porosity and inconsistent thickness.

3. Notably, the introduction of 3 ml of water into the delamination at 3 minutes and 40 seconds, concealed from the sensor by approximately 2 cm of porous polymer and retained by the inner carbon fibre glass resin layer, results in a pronounced and immediate contrast in RSA. This contrast is significant and clearly distinguishable from the healthy baseline.

8.4.1.1.3. Machine Learning applied to FMCW Radar Inspection

This section presents machine learning analytics applied to the previously mentioned FMCW Radar for composite wind turbine blade samples provided by EDF Renewables Ltd. The results demonstrated that the algorithm could classify blade types by composition and diameter differentials of 3 millimetres with over 95% classification accuracy [35]§. The methodology presents a potential solution for automated classification of surface and subsurface fault precursors in wind turbine blades and other composite materials. The procedures for experimentation and data acquisition, encompassing details about the test platform and samples, are outlined. A comprehensive data library of radar signals was compiled, featuring diverse wind turbine blade samples. These samples represented various wind turbine blade composites, each characterised by distinct inner composite structures and

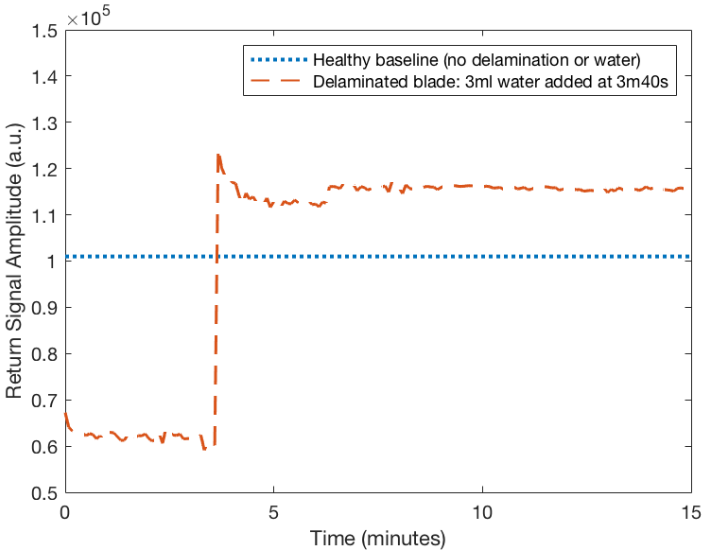


Figure 8-8 Return signal amplitude compared against the healthy baseline signal for the dry delamination and then water added at 3 mins and 40 seconds into the investigation [36]§.

physical dimensions. Subsequently, four machine learning models were trained using this extensive data library for crucial tasks such as key feature extraction and sensitivity testing.

Displayed in Figure 8-9 includes two monolithic and a single sandwich composite sample which were utilised within the investigation where both types of composite are regularly used in operational wind turbine blades. These types of composite typically make up the shell of the aerofoil shape to ensure effective aerodynamics during operation. The spare caps are the load bearing components of the structure so that the composite shells themselves have minimal high loads induced on them. This leads to the spar caps being considered as the most important segments of the structure. Typically these are made from monolithic composites via fibre reinforced plastic as displayed in Figure 8-9 A and B where sandwich composite is used for the shell as displayed in C due to its lightweight core material however sometimes does feature fibre reinforced plastics to strengthen certain areas[427]§. The material properties of the samples are presented in Table 8-3.

To acquire a sufficient number of radar scans for each sample, we conducted a raster scan using a universal robotic manipulator arm with the sensor mounted onboard. This scanning process involved subdividing the surface of the target sample into a sequence of strips. Each strip was then further divided into discrete small pixels, facilitating the FMCW sensor to aim and obtain the return signal amplitudes. The return signal of each scan captured the material properties within the specific field of view over the entire sample surface. The primary objective was to gather a robust set of radar scans from the evenly divided areas and extract

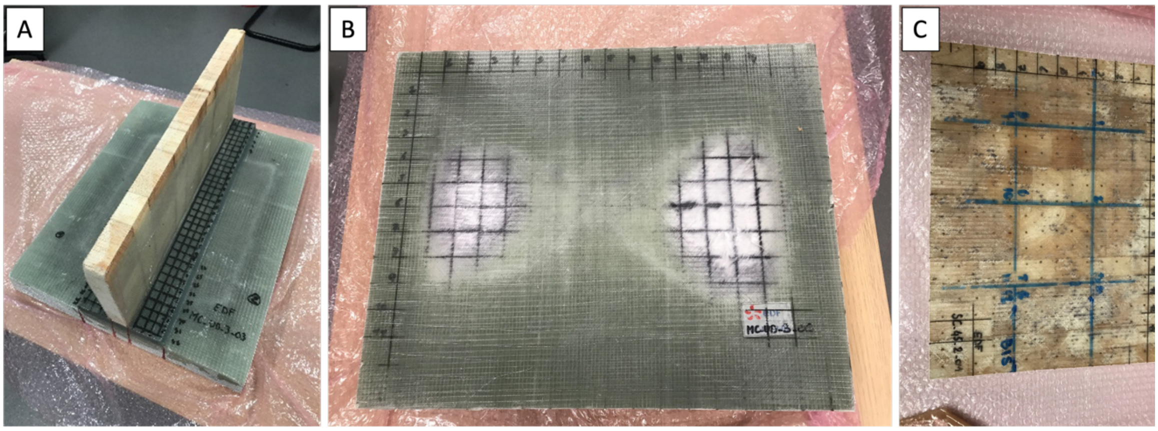


Figure 8-9 Three examples of the composite and sandwich blade composites provided. A) class A monolithic composite with adhesive bond of 48.7mm B) class B monolithic composite with manufactured dry area measuring 51.3mm thick C) Class C Sandwich composite featured with interlaminar porosity at 27.7mm thick [35]§.

Table 8-3 Key properties of the wind turbine blade samples [35]§.

Sample as displayed in Figure 8-9	Material Type	Defect type	Thickness (mm)	Measurement points
A	Monolithic	Encapsulated and single edges adhesive voids	Monolithic part: 48.7 ± 0.5	14
			Total with adhesive bond: 59.6 ± 0.1	4
B	Monolithic	Uncured Adhesive	Monolithic part: 48.4 ± 0.3	18
			Total with adhesive bond: 63.2 ± 4.3	4
C	Sandwich	Gaps between balsa blocks (1mm, 2mm, 4mm)	Total: 27.8 ± 0.7	14

a common pattern that could effectively represent this particular type of blade sample [427]§.

The antenna was positioned to ensure that the direction of electromagnetic propagation was perpendicular to the blade surface. Initially, the robot arm was manually positioned in free drive mode to face the pixel point at the top-left corner of the target sample surface, maintaining a 10 cm separation distance between the target and the antenna tip. This point served as the starting point for the first scan. The robotic arm was then programmed to move horizontally with a fixed step distance to scan the adjacent pixel points until reaching the top-right corner of the blades surface as displayed in Figure 8-10. This scanning action was repeated row by row until the entire area of the target was covered. In addition, we also collected raster scan data with the radar at various distances from the surface (10, 20, and 30 cm) to ensure an ample and diverse dataset for a more comprehensive training pool [35]§.

For machine learning, classification involves a model's capacity to accurately assign instances to their respective groups. In this study, our goal was to correctly identify the type of blade sample based on the radar return signal amplitude in the testing dataset. This allows for our library to automatically distinguish and classify sample classes.

The machine learning approaches implemented included Support Vector Machine (SVM), Bayesian Network, Decision Trees and Back Propagation (BP). SVM is a widely-used classification method that employs gradient descent to determine hyperparameters, effectively delineating distinct data groups and maximising the margin between them [428]. The separation of data points relies on various mathematical functions known as kernels. The kernel's role is to take input data and transform it into the necessary form. The Bayesian method is also a widely known probabilistic model which represents a set of variables and their conditional dependencies via a directed acyclic graph. This enables for visualisation of the probabilistic model for a domain of relationships between random variables and determining causal probabilities for scenarios and therefore is a very useful tool [429]. The BP neural network, also known as artificial neural networks is a useful tool for mapping nonlinear relationships and shows stable robustness and fault tolerance when applied to an unknown or unfamiliar system. BP stands as one of the prevailing neural network models in signal image processing and classification [430]. Decision Trees is the final popular method of machine learning tested in this segment of the thesis for NDE with the microwave sensor. The aim is to train a predictive model for estimating the value of a target variable using multiple input variables. During testing, it classifies samples by traversing from the root to a specific leaf node in the tree, where the leaf node assigns a classification to the example.

For this body of work, 3 different distances were repeated for each sample of wind turbine blade where around 600 scans were taken throughout the raster. This leads to 600 raw data signals to be collected for each class and each data point which contains a vector with 1501 dimensions representing the time domain signal returned from the target interface. For this segment of the chapter Class A, B and C represent the samples displayed previously in Figure 8-9 as a reminder. It is emphasised that whilst classes A and B share the same material type (monolithic material) they differ in thickness by 3.5mm and sample 3 is a different material (sandwich composite) with different material structure.

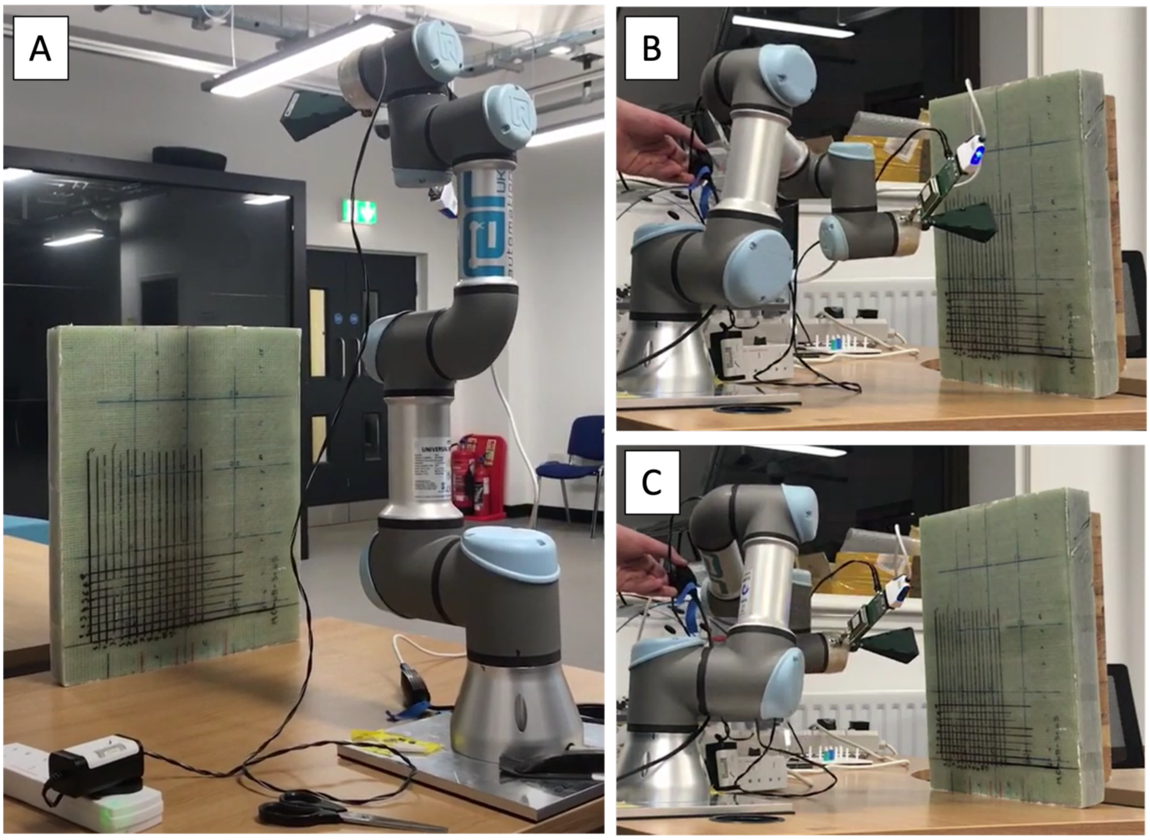


Figure 8-10 A series of images displaying the FMCW Radar setup and UR3 robot used to conduct the data collection procedure [35,427]§.

The models underwent training using 75% of the raw data and were subsequently tested with the remaining 25%. When provided with a new observation from the testing data pool, the model outputs one of three sample types. The outcomes are illustrated in Figure 8-11 through a confusion matrix, also referred to as an error matrix, offering a visual representation of the performance of various algorithms. In this matrix, each cell displays the percentage of testing data from a specific true class that the model classifies as a particular predicted class.

Principal component analysis was also used to develop further selection and dimensionality reduction to further evaluate the capabilities of different models when given compressed observation data [431]. For this dataset nine primary components were generated to achieve 95% explanation of the original variability. The overall accuracy of the algorithm in this study was calculated as the mean proportion of the correct output where the results are viewed within Table 8-4.

For this investigation we evaluate the data collected by the microwave radar sensor via post processing of the Fast Fourier Transform (FFT). This data is converted from the time domain raw signal into the frequency domain enabling key amplitude extractions to be used for

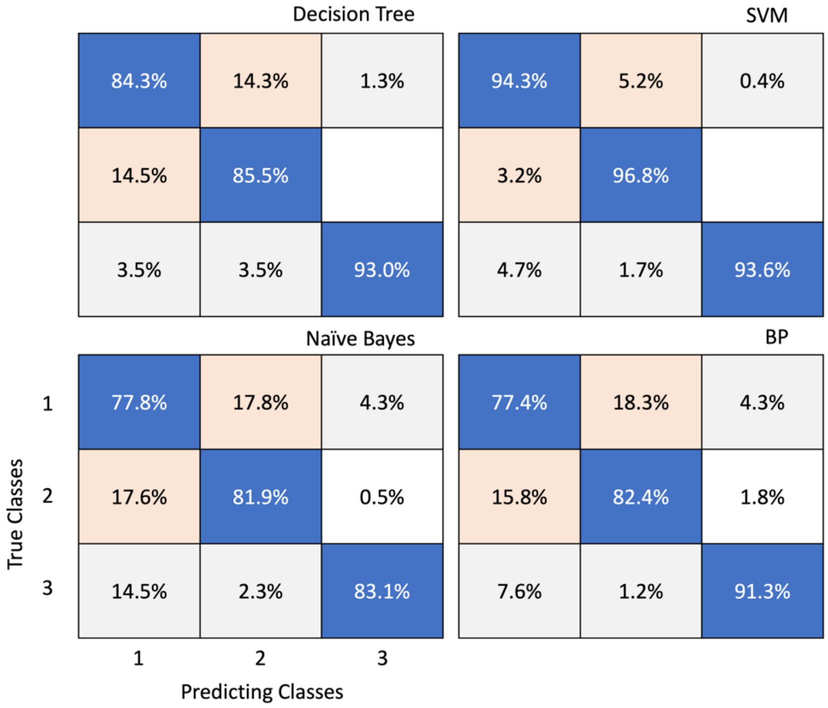


Figure 8-11 Confusion matrix highlighting each model's performance [35]§..

Table 8-4 Performance of the machine learning models with respect to the time domain datasets [35]§.

Algorithm	**Accuracy (Full Data)**	**Accuracy (Compressed Data)**
SVM	95%	91%
Naïve Bayes	80.7%	76.1%
Decision Tree	87.7%	75.6%
BP	81.7%	78.7%

Table 8-5 Performance of different machine learning models with respect to the frequency domain datasets [35]§.

Algorithm	**Accuracy (Full Data)**	**Accuracy (Compressed Data)**
SVM	98.5%	92.9%
Naïve Bayes	84.8%	82.8%
Decision Tree	88.9%	88.6%
BP	84.5%	79.3%

model training. The spectral results can be attained from the original data sets where the frequency from the FMCW radar signal changes over time. This enables us to extract and learn from the return signal amplitude in a range domain. The resolution from the radar signal results in a resolution of frequency bins which corresponds to 0.1m in air. However, this distance undergoes changes as the radar penetrates materials, with variations influenced by factors such as material porosity. This work explores the fusion of machine learning and spectral radar signals to extract the key material properties of the blade samples from our training in the classified models as displayed in Table 8-5 [35]§.

The results from the microwave data display robust integrity data analysis when using machine learning data approaches for composite material characterisation with wind turbine blades. Within Table 8-4 we can identify that SVM provides the most effective performance of all machine learning classifiers at 95% accuracy with Naïve Bayes providing the lowest, but still acceptable in many respects, accuracy of 80.7%. In addition, the results also identify the successful classification between Class A and B where the composites only exhibit a 3mm thickness difference, where class 3 differs entirely in blade structure [35]§.

Additionally, it's worth noting that while Class A and Class B samples exhibit only a slight difference in thickness (3mm), Class C blades distinguish themselves from the former two by their material structure. Given these characteristics, we anticipate that blades sharing the same composite would display similar return signal amplitude compared to those with different composites. This anticipation aligns with our model evaluation results. Illustrated in Figure 8-11 confusion matrix, across all models, when presented with test data from Class A (or Class B), incorrect predictions more frequently fall into the category of Class B (or Class A) rather than Class 3. Nonetheless, our machine learning model effectively classifies the difference between Class 1 and 2, with the SVM model achieving highly promising accuracies of 94.3% and 96.8%, respectively. Furthermore, all models demonstrate improved performance when classifying samples with a distinct material structure (Class 3). This highlights the FMCW's sensitivity and underscores the machine learning models' proficiency in extracting crucial features from radar RSA. The findings showcase the capacity to identify subtle internal variations in blade samples, a capability currently beyond the reach of contemporary externally deployed NDE technologies for composite turbine blades [35]§.

Compressed time domain data was also tested, indicating potential and flexibility in handling higher resolution signals (greater dimensions in the training data) in the future. The results showed 91% accuracy for SVM and an average accuracy of 83.5% for the other machine learning models [35]§.

Finally, the results in Table 8-5 demonstrate that majority of machine learning models display improved performance when using the extracted frequency domain of the return signal amplitude as the training data. This results in a minimum accuracy of 84.5% where SVM with a polynomial kernel function reached 98.5% accuracy demonstrating that the frequency domain provides improved feature extractions for the composite material properties. This can benefit data driven approaches to provide improved accuracy and robust characteristic in the evaluation of inspection of wind turbine blades in the future [35]§.

8.4.1.1.4. Asset Integrity Dashboard for Visualisation of Results

To improve the visualisation process and results from the FMCW radar sensor, an Asset Integrity Dashboard (AID) was created to enable for people to understand the data from the sensor much easier. Images of the AID are displayed in Figure 8-12 and Appendix 13-9 to Appendix 13-11 in addition to a live, online interactive version which can be accessed by Mitchell *et al.* [432]†. The dashboard was created within Unity 3D and HTML5 web integration. The challenges overcome from this interface included how to improve the understanding of the results from the sensor via making it more intuitive. This was achieved by making the results more visual so that someone with less understanding of the required theory of FMCW radar sensor could have an improved understanding. This allows for the AID to act as a DT of the wind turbine blade section where buttons are presented to the user on the left for different types of information.

The information within the dashboard includes:

1. Images of Actual Sample: Photographs depicting the sample undergoing twinning in the AID.
2. Sample Parameters: The provided parameters of the sample, including material composition and size.
3. Sample Schematic: A visual representation of the sample with the defect area highlighted.
4. Experimental Setup: Photographs illustrating the experimental arrangement of the FMCW with the sample.
5. Graph Overlay: Displaying all return signal graphs collectively.
6. Summary: A text-based overview summarising the detected defect.

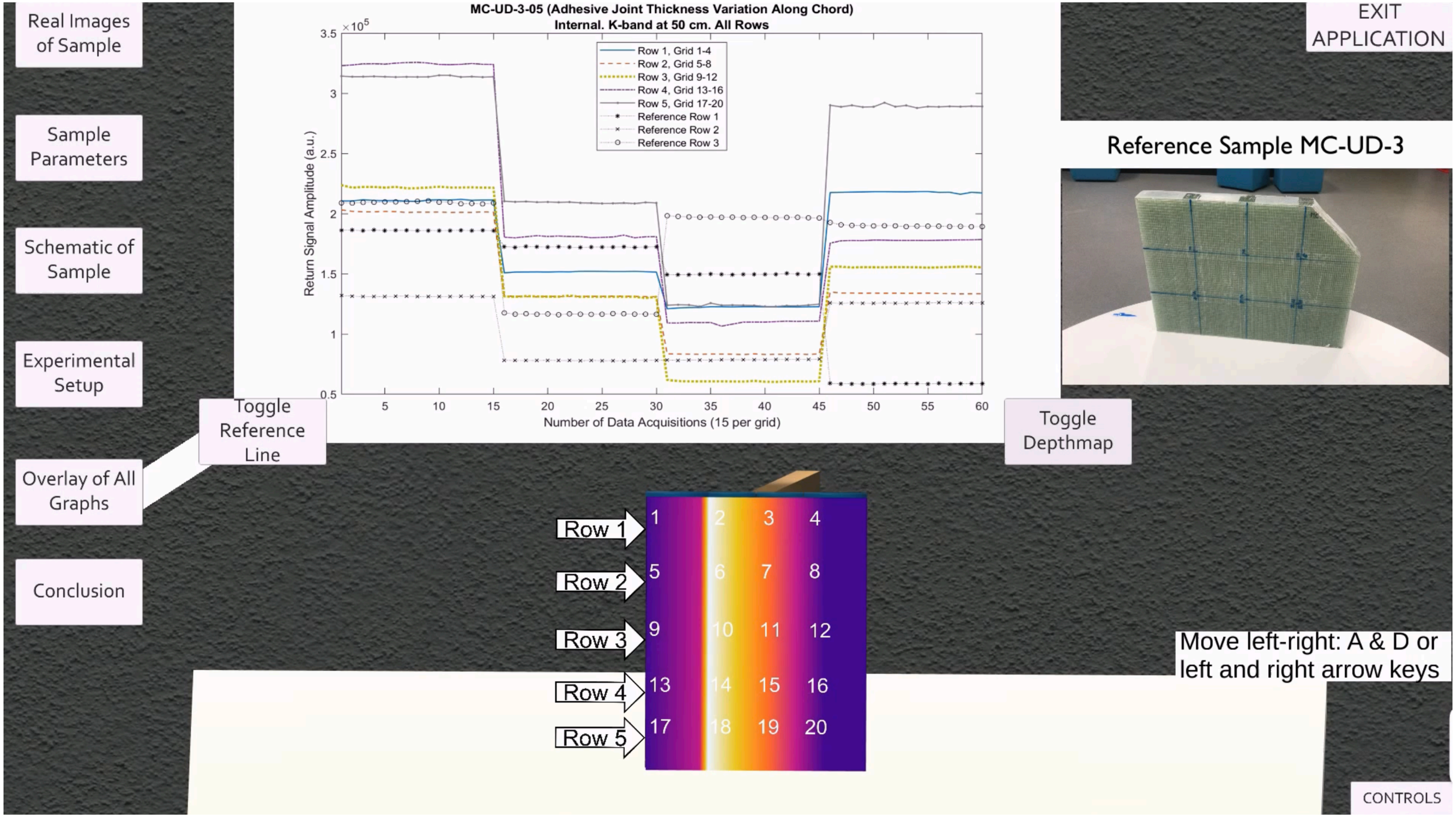


Figure 8-12 Visualisation of the asset integrity dashboard displaying data, images of the sample and a heatmap displaying a varying adhesive thickness [420]§. Appendix 13-9 to Appendix 13-11 display more views of the dashboard [432]†.

As displayed in Figure 8-12, the ‘overlay of all graphs’ button has been pressed. This displays the results for all the rows scanned on the same graph. The toggle depth map button displays a colour gradient which has been placed over the material to enable the user to understand the thickness of the material under test from all the rows. The yellow highlights the thickest area of the adhesive bond and purple displays the standard adhesive bond used. When the toggle depth map button is deactivated, the user can select each individual row and view the results on the graph individually too.

Utilising an alternative display method like this offers the advantage of a more intuitive approach to examining return signal data. Future developments in this field involve exploring additional visualisation techniques for the data (such as highlighting critical parts of the return signal) and real-time generation of graphs and models. Presently, all displayed data is generated offline in MATLAB, with only screenshots featured in the AID. Subsequent work aims to generate this information during runtime, facilitating swift remote asset integrity inspections.

8.4.1.1.5. Summary of NDE for Wind Turbine Blade Inspection

The current methods employed for NDE of wind turbine blades are both labour-intensive and expensive, primarily relying on visual inspection. In addition, an increasing number of wind farms, have a critical need to enhance the consistency and accuracy of WTB evaluations, ensuring safe access to both surface and subsurface characteristics. Addressing this demand, this section introduces a non-contact, low-power NDE approach utilising FMCW radar analysis alongside machine learning.

Results from classification models illustrate that FMCW can effectively characterise physical features of composite materials, such as thickness, achieving 92.9% accuracy with a SVM model and a full range of frequency domain amplitude for training. Furthermore, the method demonstrates the capability to discern variable surface defects, including dry zones, with high accuracy of 98.9% (SVM) and 82.9% (Naive Bayes). Additionally, FMCW analysis successfully captures subsurface defects, such as air voids of size 1mm, with over 94.1% accuracy.

In summary, this section showcases the promising potential of FMCW in capturing both physical and defect information of WTBs, while also emphasising the automation of this lightweight, compact, and low-power technology for advancing NDE inspection procedures for composites. Finally an AID interface for presenting return signal data in an intuitive manner for those unfamiliar with the technology was presented.

8.4.1.2. Civil infrastructure

Critical infrastructure forms an intricate network of systems crucial for essential services like energy, transportation, and supplies of water. Ongoing cycles of monitoring and maintenance are imperative for the sustained economic development and operational functionality of a community. Existing methods for detecting subsurface fault precursors in civil infrastructure prove inadequate for comprehensive subsurface defect detection [37]†.

This chapter introduces an analysis of complex multi-layer structures using FMCW radar sensing. Results showcase the effective use of K-band analysis in identifying embedded and obscured materials during inspections, leveraging contrasts in the return signal amplitude from the sensor. This capability extends to detecting the depth and geometry of subsurface materials, as well as identifying water ingress within materials.

Consequently, FMCW analysis offers a novel approach to non-invasive, non-contact, and non-destructive analysis of dielectric and multi-layer materials, particularly applicable to asset integrity and health monitoring in the civil infrastructure sector. This research ensures that inspection engineers have access to tools that yield quantitative and qualitative results, enabling a more effective assessment of the subsurface integrity of a structure. The FMCW sensing modality facilitates early prognostics and remedial action, reducing asset downtime and the risk of failure [37]†.

8.4.1.2.1. Context

With respect to civil infrastructure, Reinforced Concrete (RC) offers numerous advantages in construction due to its durability, versatility, and inherent fire resistance compared to other frequently utilised building materials, contributing to the creation of safer infrastructure [433]. The premature deterioration of various civil structures like highways, bridges, offshore platforms, pipelines, and dams is frequently attributed to corrosion effects. The American Road and Transportation Builders Association approximated that 37% of US bridges require repair work where 81,000 should be replaced. The cost for implementing the identified repairs on bridges is close to $164 billion, and it has been determined that these compromised structures are accessed daily by 178 million motorists [434–436]. The steel rebar, primarily composed of iron, plays a significant role in compromising the remaining useful life of these assets [437].

The degradation of reinforced concrete structures is in most cases, a result of environmental factors, including climate conditions and freeze-thaw damage. The hydration process of cement establishes a highly alkaline environment, forming a protective passive layer for embedded rebar, shielding it from air and moisture [438–440]. In the absence of this protective layer, rebar corrosion accelerates due to the infiltration of aggressive agents. Prolonged exposure to chlorides, which permeate the porous concrete through diffusion and absorption of water, reaching the rebar interface, leads to the corrosion of iron rebar. Additionally, the passive layer can be diminished through carbonation, a reaction with CO_2 [437–439].

8.4.1.2.2. Experimental Setup and Results

This section presents an experimental investigation into verifying the effective use of the FMCW radar sensor for sensing features of reinforced concretes via two key analogues. Three different investigations take place within this section across 8.4.1.2.2A and B where investigation setup and procedure is presented alongside the results for each investigation. The microwave signal captures results in the time domain, which are subsequently transformed into the return signal amplitude measured in arbitrary units as previously. Next a transformation is accomplished through the application of a FFT on the signal. An FFT is classically used as a range estimation where BIN numbers are used to represent the distance from the radar to the target. However, this section identifies that the FFT reveals key characteristics within the material properties [441]. Baseline measurements were taken into consideration within each of the investigations presented in the following subsections A and B.

A. Embedded Material Analysis of Metals in Sand

This investigation assesses the FMCW radar sensitivity to the depths and geometries of several metallic interfaces buried in sand. A diagram of the investigation is displayed in Figure 7-13. To evaluate the return signal amplitude for diverse target geometries, a copper sheet was compared with a copper rod at the same buried depth. The distance from the sand

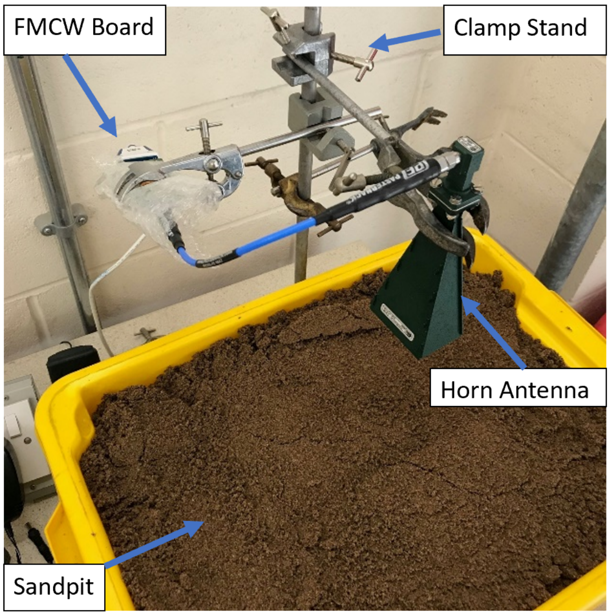


Figure 8-13 Investigation setup of sandpit area and equipment [37]†.

surface to the antenna remained constant at 10 cm throughout the experiment, ensuring that variations in the observed return signal amplitude were attributable to the variables under examination: depth, material type, and target geometry. Each target shape was positioned both on the sand surface and at depths of 5 cm, 10 cm, and 15 cm.

Aluminium, brass, iron and steel were utilised for variations in shape and size to establish FMCW sensitivity. The K-Band FMCW radar was set to complete a frequency sweep of 24-25.5 GHz for a chirp duration of 300 milliseconds with the same radar properties as previously discussed in Table 8-1.

The results within Figure 8-14 display that the return signal amplitude for the embedded material decreases incrementally as a function of increasing burial depth. This is observed for both Figure 8-14 and Figure 8-15 for copper sheet and copper rod. This can be attributed to the sand absorbing the signal from the radar resulting in a direct relationship between the return signal amplitude reduction as a function of sand depth for the copper. The results indicate the effective detection of buried copper when concealed at different depths.

It can be noted that Figure 8-14 and Figure 8-15 display a noticeable difference in the return signal amplitude at a depth of 15cm where it is expected that the maximum penetration depth of the radar was identified. This variance may stem from the accumulation of moisture within the sandpit, possibly influenced by natural atmospheric humidity during the investigation

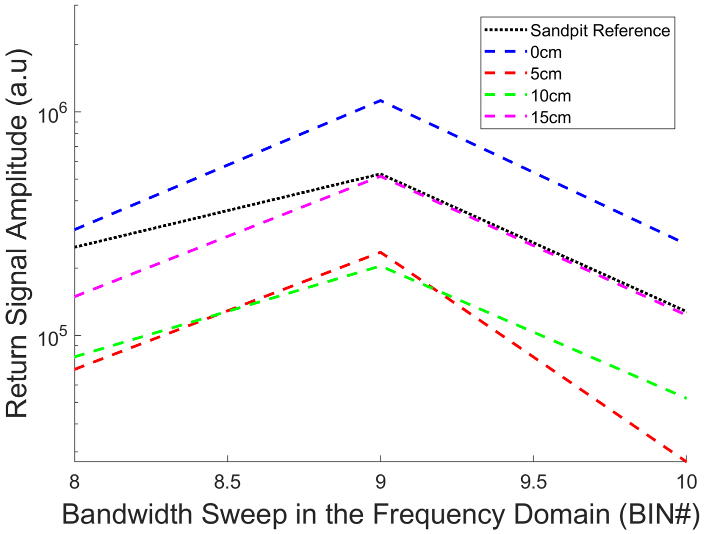


Figure 8-14 Return signal amplitude for embedded copper sheet buried at different depths within sandpit [37]†.

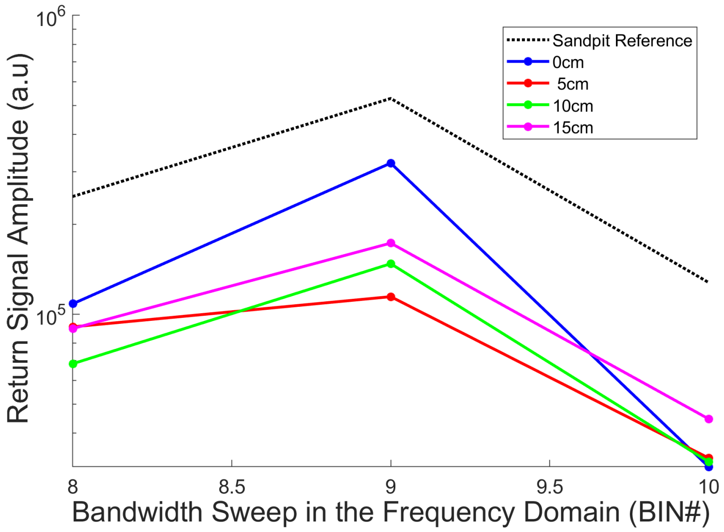


Figure 8-15 Return signal amplitude for embedded copper rod buried at different depths within sandpit [37]†.

which took place over two days. To address and comprehend this disparity, future investigations would involve heating the sand between experiments to eliminate any residual humidity.

An investigation of the shape of embedded material is next considered. The results for the copper sheet and copper rod are compared where the results display that as expected, the copper sheet returns an increased return signal amplitude when compared to the copper rod. The dashed lines within Figure 8-16 present the results for the copper sheet where an

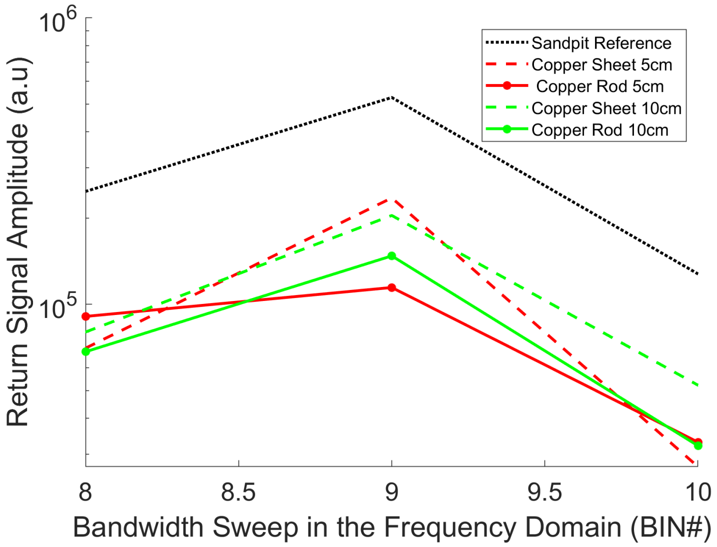


Figure 8-16 Return signal amplitude comparison of copper sheet and copper rod at 5cm and 10cm [37]†.

increased return signal can be seen. The signal is therefore sensitive to target geometry where as expected, a flat metal target reflects more of the incident energy than a cylindrical rod.

B. Embedded Material Analysis of Darney Sandstone

For this investigation, the return signal amplitude is measured for metals embedded within Darney Sandstone. Two apertures with a diameter of 38 mm were drilled, as illustrated in Figure 8-17, to facilitate the placement of materials for testing. A metal ruler and a drill bit were subsequently introduced at different points during the experiment to assess the FMCW radar's sensitivity to these metals. Lastly, 3ml of water was applied to the aperture's edge,

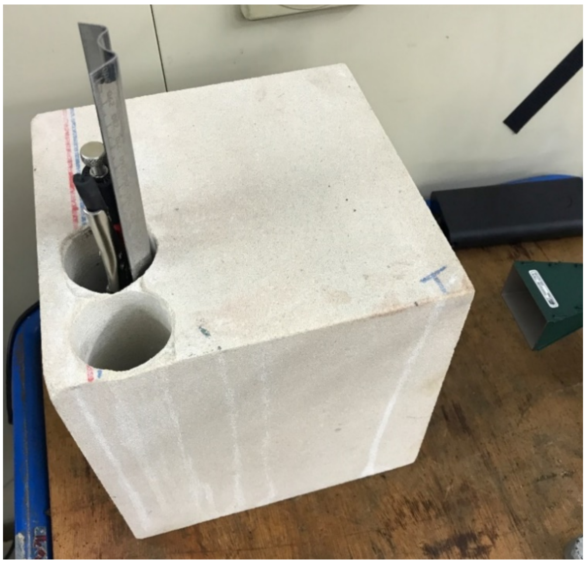


Figure 8-17 Analysis of embedded materials in Darney Sandstone (20x20x20cm) with emphasis on antenna positioning and insertion of a concealed object. The antenna is observable to the right of the sandstone [37]†.

ensuring it fell within the radar's target area. The separation distance between the antenna and the target was maintained at 10 cm.

A summary of the results and procedure is displayed within Table 8-6 with analytical results displayed in Figure 8-18 with corresponding positions of time during the investigation. Position 1 displays the results for the hardened steel cylinder drill bit which has a diameter of 2cm and was inserted at the rear edge of the aperture where the observed return signal amplitude and phase increases from the established baseline. The results from position 2 showcase the return signal when the drill bit was then repositioned closer to the antenna whilst still concealed within the aperture where the return signal again increases. Position 3 presents the results for the stainless-steel ruler which was positioned within the aperture. This resulted in a further increase in the return signal amplitude and a decrease in the phase shift. A reorientation of the stainless-steel ruler took place at position 4 showcasing a decrease in the phase shift and increase in return signal amplitude. 3 millimetres of water was deposited within the aperture using a dropper at position 5. The detected changes in return signal amplitude and phase unfold gradually as capillary action and gravity facilitate the spreading of water within the sensor's field of view. This experiment highlights the remarkable sensitivity of the FMCW radar sensor to embedded metals and water infiltration within a porous sandstone target.

Table 8-6 Procedure and description of the results displayed in Figure 8-18 [37]†.

Position	**Description of parameter and resulting signal analysis**
1	Drill bit included in the aperture, obscured by sandstone. Resulting signal increases from baseline
2	Drill bit moved towards the sensor but still within the aperture, return signal amplitude increases further
3	Stainless steel rule added within the aperture. Significant increase in signal and phase shift identified
4	Stainless steel rule re-orientated to concave side, return signal increases further and phase shifts again
5	Steel ruler and drill removed. Water added to wall of aperture, return signal dynamically changes as water seeps into pores of sandstone, phase shift increases and steadily decreases

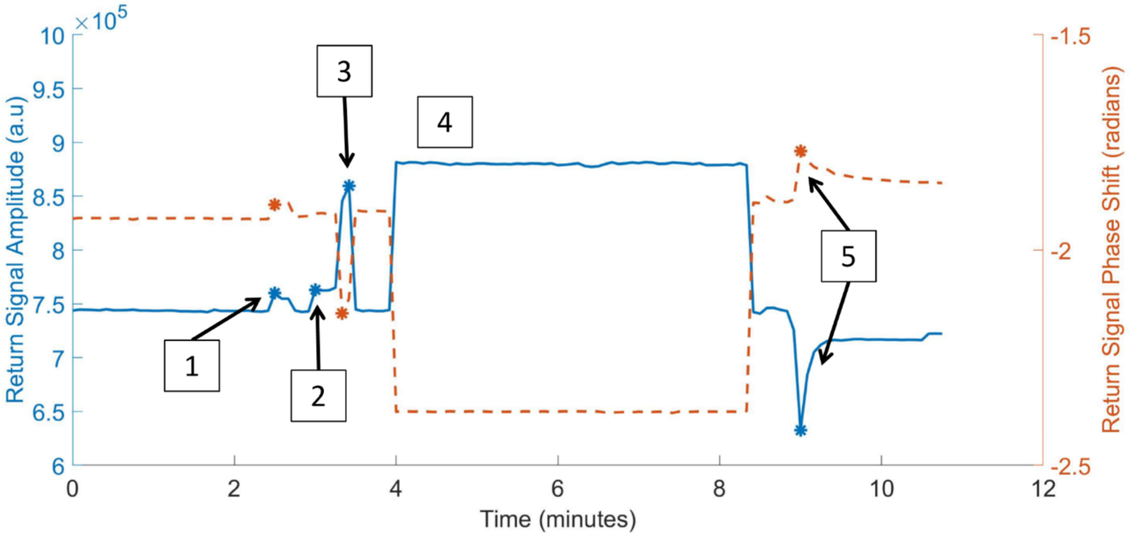


Figure 8-18 The return signal amplitude and phase shift against time in minutes for the embedded materials within the Darney sandstone material [37]†.

8.4.1.2.3. Summary

This research demonstrates the ability for the microwave sensor to detect key asset integrity measurands and validates microwave sensing as a novel tool for the detection of subsurface properties and dynamical conditions. In summary, this section presented the results of experiments with embedded rebar analogues with different shape and depths in sand and sandstone. In addition, the radar sensor was sensitive to obscured metals and small volumes of water ingress which can act as a precursor to corrosion onset and will be very useful in detecting in the future.

8.4.1.3. Overhead Line Detection

Globally, overhead transmission lines are strategically positioned to facilitate the long-distance transmission of electrical energy. These expansive networks comprise multiple electrical cables suspended above by pylons. In England and Wales alone, the infrastructure encompasses more than 90,000 pylons and spans 7,000 kilometres of high-voltage overhead lines, necessitating regular inspection and maintenance [442]. Safety considerations for technicians involved in the inspection process encompass challenges such as accessing remote locations, contending with adverse weather conditions, and performing inherently high-risk tasks at elevated heights [442].

Overhead transmission lines adhere to specific standards, such as IEEE standard 524–2016, which delineates commonly employed mechanisms for protective grounding. It also specifies different components and mechanisms for introducing sag in overhead line wires based on the tension requirements of the conductors [443]. Despite these standards, catenary lines encounter challenges, particularly in the fluctuation of sag, leading to line breaks and reduced energy efficiency. Variations in sag can be attributed to climatic and seasonal changes, where cables stretch in warmer temperatures, contract in colder conditions, or accumulate ice during winter, further contributing to sag in the line [444]. These issues often arise in remote and hazardous climates, necessitating engineers to cover significant distances for inspections in challenging terrains [445]†.

This subsection investigates the FMCW Radar sensor for the measurement and detection of overhead transmission line sag from the ground. The positive results can alleviate the need for overhead linesmen working at height in hazardous conditions. Key contributions of this segment include a proof-of-concept investigation to evaluate the successful detection of overhead lines for pylons with different overhead line heights and detection of the overhead line sag along the length of the cables between a pair of pylons [445]†.

8.4.1.3.1. Methodology

A Mileseey laser distance meter (serial number A200957904) was utilised to measure the heights of the overhead line. This meter could measure a maximum range of 120 m ± 2 mm. A challenge existed in measuring the heights of the cables accurately, so the heights were measured at the bottom edge of each insulator when positioned directly below the cable, which provided a large target to aim the laser at. Table 8-7 and Figure 8-19 presents

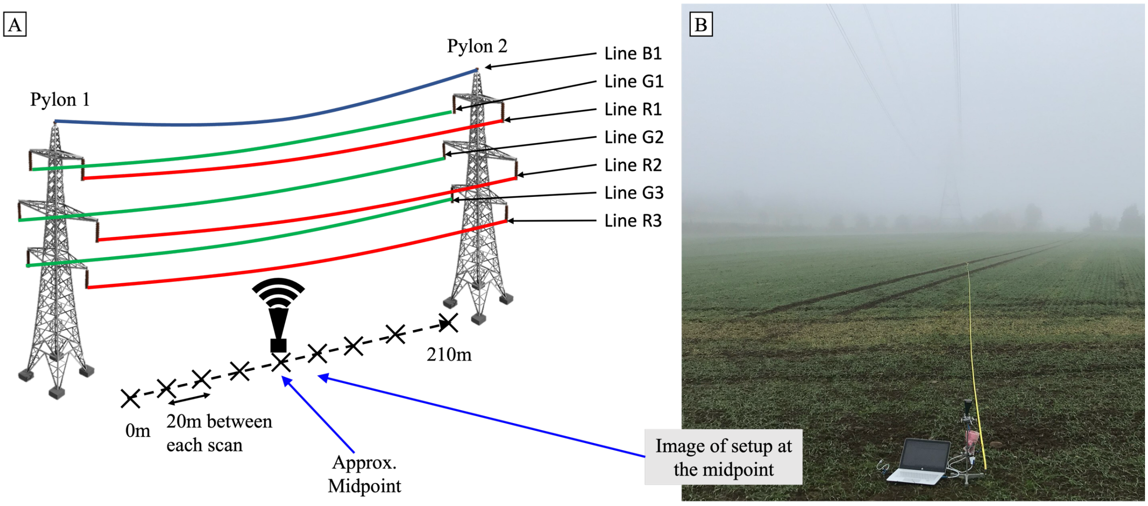


Figure 8-19 A. The investigation setup displaying the radar sensor positioned between the pylons in the first investigation and iterative positions when calculating the overhead line sag B. Radar setup between cables highlighting foggy weather conditions which the FMCW radar can overcome when compared to visual cameras and laser rangefinders [445]†.

Table 8-7 The mean distance from the laser rangefinder to the insulator is calculated for each overhead transmission line. Refer to Figure 8-21 for the naming convention of each overhead line [445]†.

Pylon	***Overhead Line***	***Range (m)***	***Elevation above sea Level (m)***
1	R3	16.578	123.578
	R2	19.935	126.935
	R1	24.221	131.221
	B1	26.524	133.524
2	R3	14.358	120.358
	R2	18.276	124.276
	R1	22.164	128.164
	B1	25.727	131.727
3	O3	38.042	146.042
	O2	45.804	153.804
	O1	53.487	161.487
	K1	X[a]	X[a]
4	O3	37.494	150.494
	O2	44.133	157.133
	O1	103.567	216.567
	K1	X[a]	X[a]

X[a.] Unable to obtain a measurement for cable heights as it was too difficult to aim the laser range finder at the target consistently as it was too high.

the results from the laser rangefinder and highlights the naming conventions for the overhead cables.

The same FMCW radar setup was used as previously presented within Figure 8-4 and Table 8-1. The electronics was linked to the horn antenna through a conventional waveguide. The FMCW electronics connected to the laptop through a serial port cable, drawing power from the laptop's USB port, which utilises a buck booster to supply the necessary voltage. The laptop consistently executes a MATLAB script, continuously recording data received from the FMCW radar sensor.

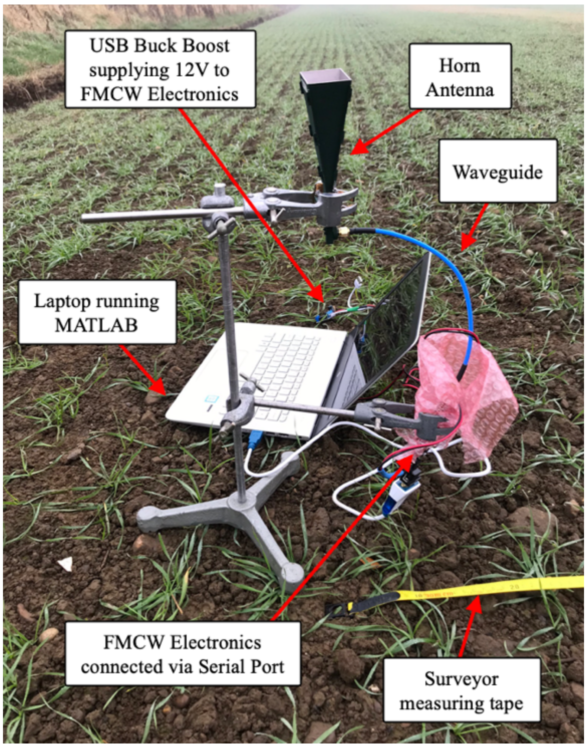


Figure 8-20 Microwave sensor arranged in conjunction with other equipment, including a clamp stand, laptop, and surveyor measuring tape [445]†.

8.4.1.3.2. Detection of Overhead Line Heights

The objective of this investigation was simply to identify if the radar sensor could detect the overhead cables and identify if the sensor could detect cables at increased heights. Figure 8-21 displays the segment of overhead lines which were evaluated against the transceiver. It can be identified that the overhead lines across pylons 3-4 were at increased heights compared to pylons 1-2. The radar was positioned directly underneath pylons 1-2 at the trough of the cables to inspect the heights of cables R3, R2, R1 and B1 and on a separate occasion positioned at the trough between pylons 3-4 to inspect cables O3, O2, O1 and K1. The results of this investigation are displayed in Figure 8-22. The graph presents the converted return signal amplitude received at the radar sensor via the FFT. Each annotated peak represents the successfully detected peaks where the BIN number represents the distance due to the time of flight from the sensor to the overhead line. Under the designation 'Test 1', the overhead lines R3, R2, R1, and B1 are distinguishable when compared to the recorded sky baseline. In the case of 'Test 2' results, overhead lines O3, O2, and O1 can be detected against the sky baseline. Furthermore, these findings confirm that the overhead lines connected to pylons 3 and 4 are positioned at greater heights compared to those associated with pylons 1 and 2 [445]†.

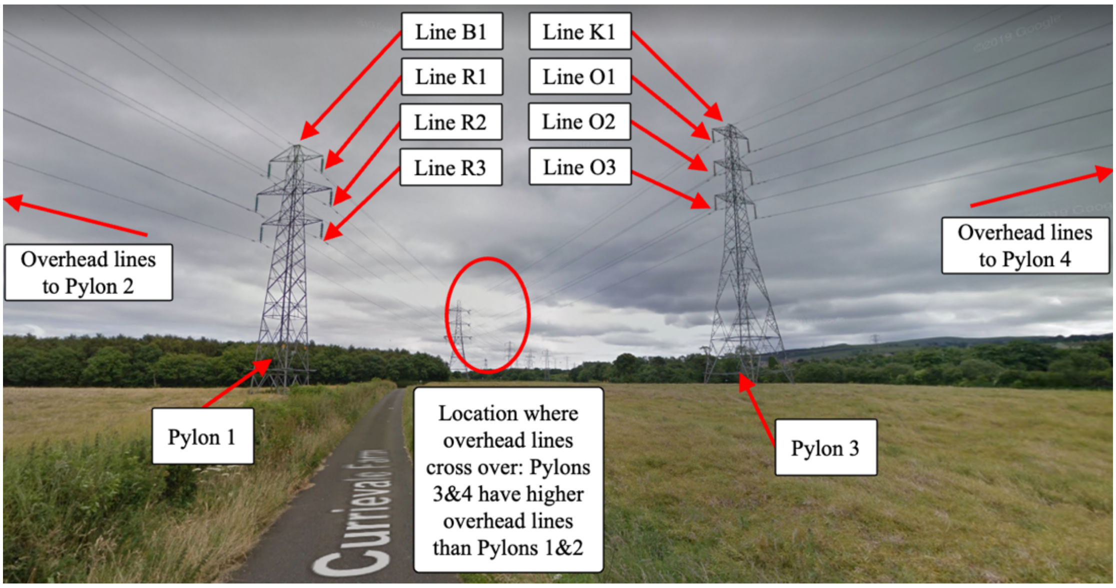


Figure 8-21 Diagram highlighting overhead line height differences between the set of pylons under investigation [445]†.

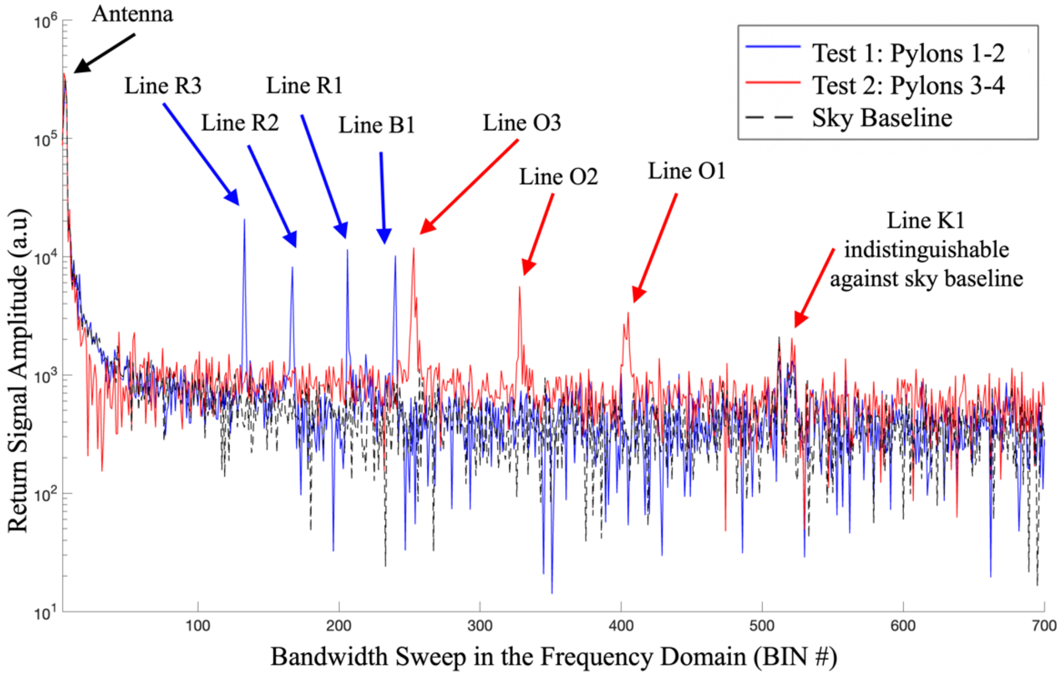


Figure 8-22 Graph displaying the accurate detection of overhead line heights for pylons 1-2 and 3-4 [445]†.

The peak observed at 500 BINs is a feature inherent to the antenna, and it is similarly evident in the sky baseline. Therefore, an annotation labelled “indistinguishable” is applied where K1 would typically be anticipated. In contrast, discernible deviations from the sky baseline are evident for the other overhead lines, signifying the successful detection of these lines.

8.4.1.3.3. Inspection of the Sag in Overhead Lines

During each scan along the overhead transmission line, the FMCW radar sensor acquires the return signal amplitude and transforms this data into a FFT. As illustrated earlier in Figure 8-22, each peak in this graph corresponds to a detected overhead transmission line, with the BIN number indicating the time of flight from the radar to the cable. Consequently, this yields a distance measurement.

These peaks correspond to a range due to equation (7-1):

$$Range = \frac{BIN \times c}{2 \times BW} \tag{8-7}$$

The range equation is used to calculate the values presented in Table 8-8 and presented graphically in Figure 8-23 where BIN denotes the identified peak for the transmission line within the frequency domain's bandwidth, where c represents the speed of light, and BW represents the bandwidth of the frequency at 1.5 GHz.

Table 8-8 Range detected from the microwave sensor to the overhead line detected at positions along the overhead line as presented in Figure 8-19A [445]†.

Distance along overhead line (m)	**Range from Radar to Overhead Line (m)**			
	G3	***G2***	***G1***	***B1***
0	17.888	21.586	25.482	29.180
20	17.188	20.786	24.683	28.280
40	16.589	20.086	24.083	27.581
60	15.589	19.087	22.984	26.382
80	14.390	17.888	21.785	25.083
100	13.291	16.788	20.586	23.884
120	12.891	16.389	20.186	23.484
140	13.091	16.589	20.486	23.684
160	14.190	17.688	21.485	24.783
178[a]	14.890	18.487	22.285	25.682
200	15.290	18.887	22.584	26.082
210	14.990	18.587	22.285	25.882

For safety reasons and constraints inherent in the laser distance meter as previously discussed when aiming the sensor, there are difficulties in validating the heights of overhead line sag within the range of 20-200m. This limitation arises from the cables being too thin to obtain a reading on the laser distance meter. Nevertheless, a comparison of the results has been established for the points where the overhead lines are connected to the insulator and are presented in Table 8-9.

The resulting accuracy, expressed as a percentage, is outlined in Table 8-10 when comparing the laser distance meter with the FMCW Radar sensor. These findings reveal an average accuracy of 95.5% when utilising the FMCW radar sensor as a range meter and comparing the results to the laser distance meter.

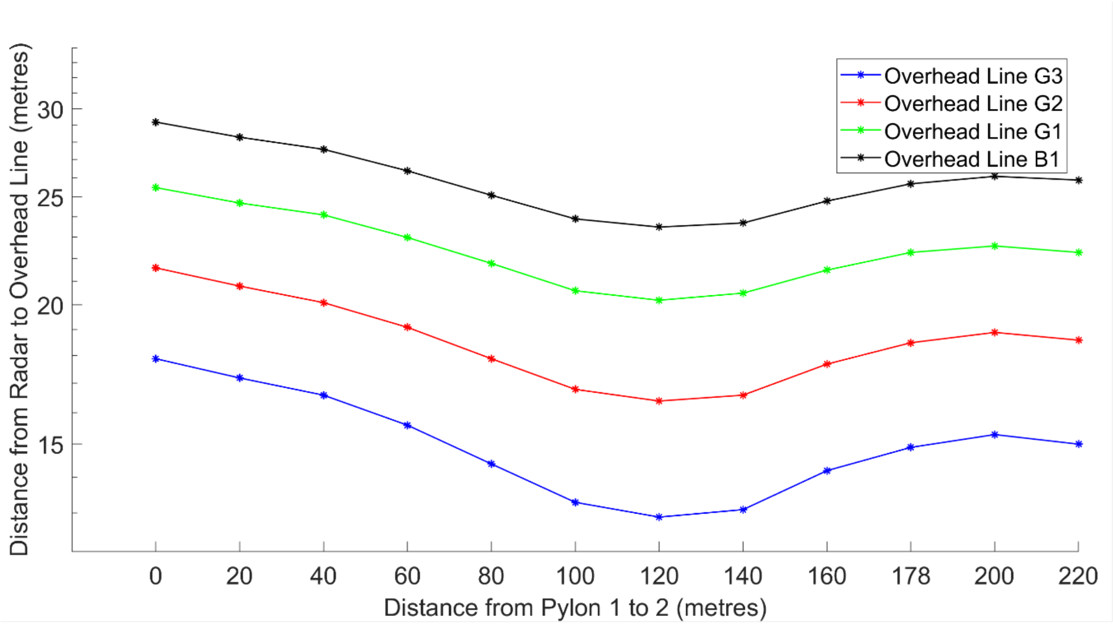


Figure 8-23 Peaks from Table 8-8 presented in a graphical format highlighting overhead line sag between pylons 1-2. Trough identified at 120m [445]†.

Table 8-9 Distance measurement to the overhead transmission line using both the FMCW radar sensor and laser distance meter [445]†.

Distance along overhead line (m)	**Method of measurement**	**Range to Overhead Transmission Line (m)**			
		G3	***G2***	***G1***	***B1***
0	Laser Range Meter	16.578	19.935	24.221	26.524
0	FMCW Radar	17.888	21.586	25.482	29.180
210	Laser Range Meter	14.358	18.276	22.164	25.727
210	FMCW Radar	14.990	18.587	22.285	25.882

Table 8-10 Comparison of accuracy with the laser distance meter, expressed as a percentage [445]†.

Distance along overhead line (m)	**Accuracy (%)**			
	G3	***G2***	***G1***	***B1***
0	92.68	92.35	95.10	90.90
210	95.78	98.33	99.46	99.40

Furthermore, we can qualitatively confirm the effectiveness of the FMCW radar sensor in detecting the sag in overhead lines for Pylons 1-2. This is evident in Figure 8-23 at 120m, highlighting the successful detection of the overhead line sag, positioned at the midpoint between the pylons.

8.4.1.3.4. Summary and Conclusion

This subsection proposes a solution aimed at addressing challenges associated with the inspection and maintenance of overhead transmission lines. The presented solution aims to reduce the need for engineers to work at elevated heights and operates effectively regardless of dynamic weather conditions. The success criteria for this investigation included achieving a high level of accuracy against a known measurement device such as a laser rangefinder. Utilisation of the laser rangefinder also presented a challenge when measuring the sag too which the FMCW radar may overcome too. The small surface area of the metal conductors meant that the human was unable to measure the height of the overhead line cable at points between the pylons. The only segment that could accurately be measured was at the insulators at each end of the pylon. This challenge becomes more difficult in the slightest of winds due to the gallop created on overhead lines too [445]†.

Additionally, a static investigation has been conducted to evaluate the FMCW radar sensor's capability in identifying and measuring the height of overhead transmission lines. A secondary investigation focused on assessing the detection of sag in overhead lines. The results confirm the sensor's effectiveness in detecting overhead line cables, demonstrating the capability to identify multiple lines in a single scan, including the detection of sag in overhead lines. Notably, the solution exhibits an average accuracy of 95.5% when compared against a laser rangefinder for measuring the height of overhead lines at the main spar on the pylon [445]†.

8.4.2. Foresight Monitoring

Robotic platforms possess high programmability, scalability, and versatility, enabling them to perform various tasks, including IMR. Mobile robotics, characterised by fewer operational constraints, offer enhanced flexibility, allowing operation at heights, in hazardous areas, and for repetitive tasks. CPS facilitate the rapid adaptation and repurposing of robotics and artificial intelligence to address emerging challenges within the CPS domain.

A significant challenge in robotics involves establishing effective partnerships in diverse areas, such as shared workspaces and BVLOS. Existing sensing methods are confined to visual line of sight, unable to capture data beyond obstacles like doorways or walls. Consequently, robots lack the ability to sense whether it's safe to open a door. Moreover, if a robot could sense beyond a door, it could proactively update safety measures in anticipation of upcoming tasks, such as a human entering a shared workspace. There may also be non-visible threats which may obscure the line of sight too such as transparent glass doorways or the inclusion of environmental variables via opaque conditions including smoke, steam and mist. In addition, mobile robots are required to be mobile in a wide range of environments, especially environments that are not designed for their use such as uncertain ground conditions found on earth or in space [446]. To navigate effectively, a robot needs to integrate additional sensors for diverse sources of information, using this data to make informed decisions about its navigation. In the context of autonomous mobile robots operating in unstructured and ambiguously defined environments, the condition of the ground is pivotal and often a leading factor in failures. For instance, the presence of ground water in the operational area serves as a notable example of failure and also in the opposite example where an abundance of sand is present [399]. For both cases, this could highlight boggy terrain which could lead to the robot becoming stuck such as within a field mission where a Clearpath Warthog became stuck when the terrain changed from winter to summer resulting in significant boggy terrain as displayed in Figure 8-24 [447]. *Foresight monitoring aims to enhance situational awareness by accessing previously unavailable data, identifying visual and non-visual variables, and detecting elements that were previously undetectable by robots. The primary goal is to uncover potential factors that could pose a threat to the mission.* This will address key themes, displayed in Figure 8-25, encompassing safety, trust, and resilience, which impede the continuous deployment of CPS therefore, this section looks to foresight monitoring with the aim to reduce risks in these challenge areas to increase the robustness of autonomous operations.

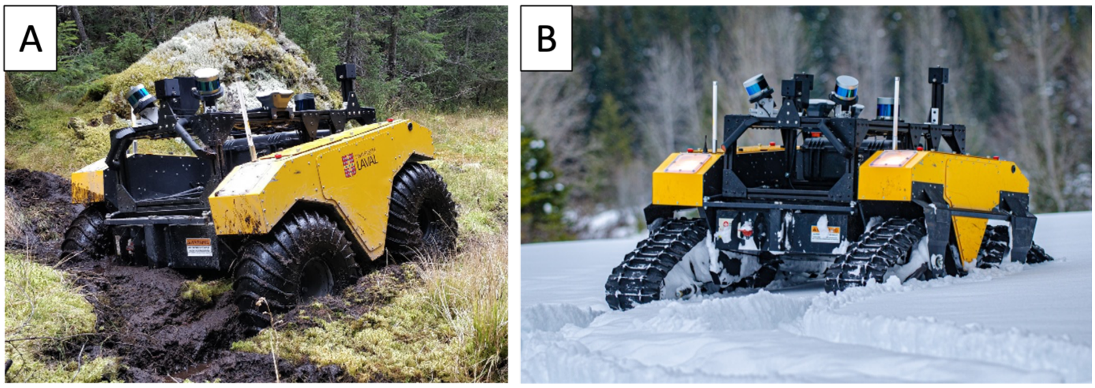


Figure 8-24 Clearpath Warthog navigating within extreme environments where A presents the robot stuck in a boggy area of terrain and the robot navigating successfully in deep snow. Albeit A displays a wheeled robot and B displays a tracked robot, there are the same versions of the underlying vehicle [447,489].

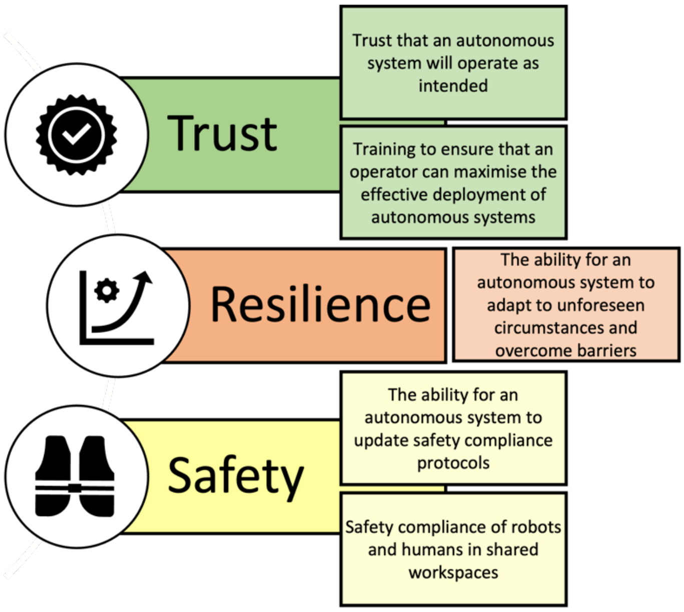


Figure 8-25 Primary obstacles hindering the implementation of fully autonomous systems, alongside examples of challenges [368]†.

8.4.2.1. Human and Through-door Detection

Currently, the navigational systems of robots mainly operate within visual line of sight to avoid different obstacles such as walls, personnel and objects. Two key challenges exist in this common scenario where 1) robotic navigational sensors are unable to detect and distinguish between objects, personnel and walls to improve the decision and safety of the mobile platform and 2) robots are limited by a visual line of sight approach where they are unable to see beyond the immediate environment. For example, if a robot could see beyond the limits of a doorway, then it could decide on whether it is safe to enter a room in advance of actioning the movement [368]†.

This section assesses the application of the previously discussed FMCW radar sensor for through-door inspection with the aim to detect metal, humans, and infrastructure obscured from the line of sight to enhance situational awareness of robotic platforms. The results validate the sensor's efficacy in detecting objects BVLOS such as behind a closed doorway. This introduces an approach to enhance safety compliance in robots through proactive foresight monitoring. The sensing modality enables for real-time decisions to be made by a robot including examples such as “Is there a human on the other side of a doorway?” and “Is there enough space for a robot to access beyond the initial doorway?”. To evaluate the low-power and non-contact sensing solution, an investigation for through door detection has been created to demonstrate that the sensor can detect a human through a wooden doorway (beyond visual line of sight) versus metal sheet and a composite material. With this newly obtained information, a methodology for a layered architecture to safety compliance is also proposed [368]†.

A summary of the related work for challenges which LiDAR must overcome and challenges which other through-wall sensing methods exhibit is presented in Appendix 13-12 Related Work within Foresight Monitoring: LiDAR and Through Wall Detection. In summary, two key challenges are required to be addressed in the state-of-the-art. LiDAR is a well-known and first choice sensor for navigation within robotic platforms. However, challenges are faced as the sensor is unable to detect and distinguish obstacles through solid doors, and the sensor is unable to detect glass doors which exist. Secondly, current methods of through wall detection are unable to detect and distinguish the presence of a human versus a common object. This section aims to overcome this issue via the microwave sensor where a X-band radar sensor was utilised due to opportunities which exist via a low power, compact sensing mechanism [368]†.

8.4.2.1.1. Methodology

Implementing a layered safety compliance approach is pivotal for fostering a productive work environment with a focus on ensuring the safety of robotic and autonomous systems. Leveraging foresight sensing enables a strategic response, providing the robot with heightened operational awareness ahead of events such as a human entering a workspace. Figure 8-26 illustrates the tiered safety compliance scenario involving autonomous robot operation in an environment where a human enters, as outlined in the following bullet points:

- In the absence of humans in the room, the robot continues its optimal autonomous operation as there is no detection of human proximity alerts.

- Utilising foresight sensing with through-wall or through-door detection, the system identifies a human near the doorway. This triggers an adjustment in safety standards, causing the robot to operate at 50% speed in anticipation of the human entering the workspace.

- Now that the human is within the same environment (or room). If the human approaches within a 3-meter range within the robot's operational area, the autonomous system reaches the 3rd tier threshold, prompting the robot to pause autonomous operations to ensure the safety of both the RAS and the human.

- Once the human moves beyond the 3-meter range, the autonomous mission resumes, ensuring a seamless continuation of operations.

For this investigation, when compared to previous cases using the FMCW radar sensor, a X-band sensor operating from 9.25GHz to 10.75GHz with a frequency sweep of 1.5GHz across 1501 frequency points and a sweep time of 0.3s was deployed. The X-band provides a lower frequency which penetrates through some less dense materials more easily such as wood. The following presents the methodology for the three different conditions where the door is closed and the material under test includes the metal sheet, composite material and human positioned beyond the doorway whilst the radar sensor is facing the door, however, does not have direct visual line of sight to the material. Several positions were used beyond the doorway to corroborate the results. The materials under test consisted of a human where the target interface included the legs at knee height, a metal sheet and composite material from a segment of a wind turbine blade. The materials under test were positioned at the different 1m iterations from 50-700cm where 8 scans were recorded within each run of the investigation. The sensor was positioned facing the wooden doorway on the outside of the room. The doorway consisted of a wood-stained pine veneer with honeycomb inner measuring 4.4cm thick displayed in Figure 8-27A. The composite material measured approx. 78cm × 32cm and the metal sheet measured 72cm × 108cm × 2mm and is displayed within Figure 8-27B.

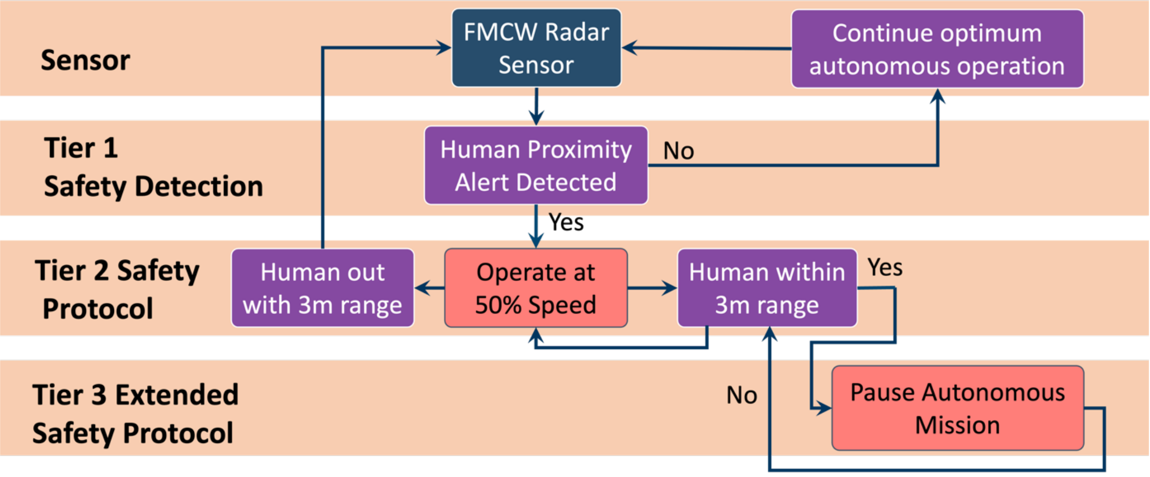


Figure 8-26 The methodology involves employing a tiered approach to ensure safety compliance, wherein a sensor is utilised to identify human presence and respond accordingly based on the fulfilment or non-fulfilment of specific thresholds [368]†.

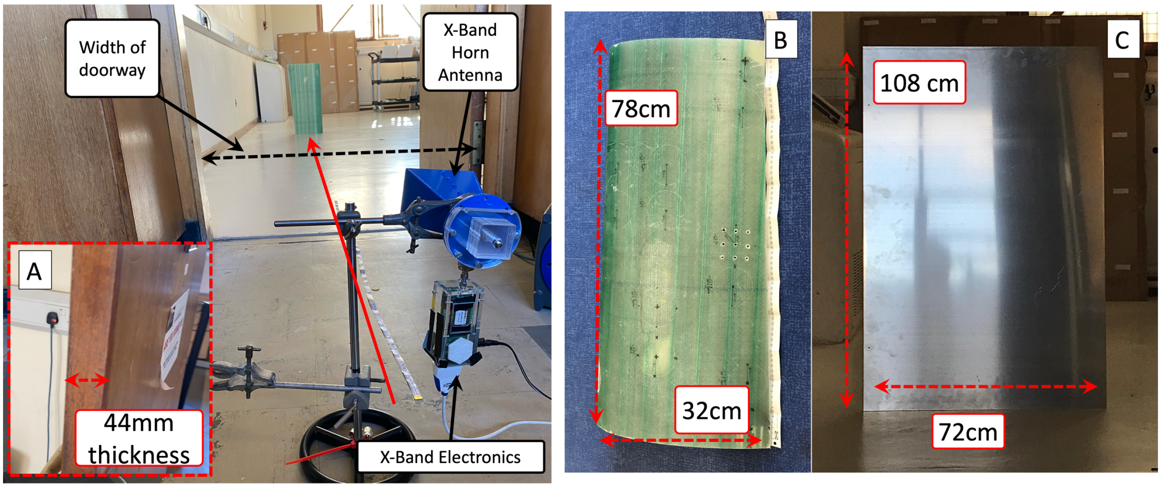


Figure 8-27 A. Investigation setup highlighting the equipment and thickness of the solid door. Materials under test presented where B displays the composite material and C presents an aluminium metal sheet [368]†.

8.4.2.1.2. Results

Firstly, the investigation setup was implemented to determine the baselines which are presented within Figure 8-28A displaying the return signal for the open door (dashed line) and closed door (solid line). Each BIN number corresponds to a time of flight from the sensor to the target. Baseline 1 presents the results for when the door was open and displays a singular peak at BIN 76. Baseline 2 presents peaks at BIN 14 and BIN 76, resulting in detection of the doorway and detection of the wall at the back of the room. The detection of the wall is verified within baseline 1 measurement.

For the verification of successful detection of metal, the sheet was positioned at 50cm (in front of the door) and 200cm to 700cm. The outcomes observed at a distance of 50cm, situated in front of the door, are not shown in this graph. This omission is attributed to the substantial peak observed, which contrasts significantly with the results presently showcased in Figure 8-28B. At a distance of 50cm, the metal sheet generates a prominent peak that poses a challenge in visualising the other individual peaks beyond the doorway. This arises from the metal sheet acting as an ideal reflector of the signal, obscuring the distinct peaks in the data. The labelled peaks in Figure 8-28B correspond to successful detections of the metal sheet.

The composite material was then positioned in the same positions where the results are displayed in Figure 8-29A. This material has contrasting properties against that of a human and metal sheet as the composite material is dielectric and is from the segment of a wind turbine blade. The results present a red box which zooms in to display the additional peaks which are a result of the successful detection of the material.

A human was then placed at the same positions as discussed earlier in this investigation, and the corresponding outcomes are illustrated in Figure 8-29B. Analysis of the data reveals a decrease in the return signal amplitude for the human compared to the metallic sheet. This reduction is attributed to the smaller surface area of the human and the human's characteristic as a dielectric material, resulting in less signal reflection to the sensor. Although the anticipated peak at BIN 54, consistent with previous results, was expected for the human, an anomalous reading occurred where the human was not detected compared to the baseline.

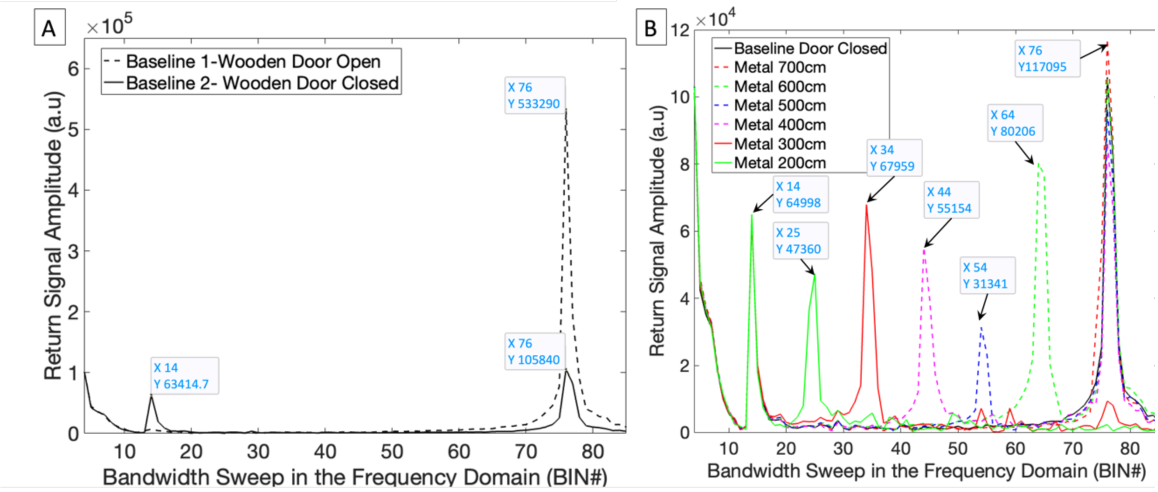


Figure 8-28 A. Baselines established from the microwave radar sensor where the doorway is open is baseline 1 and closed in baseline 2. B. FMCW radar response for metal sheet positioned beyond the doorway [368]†.

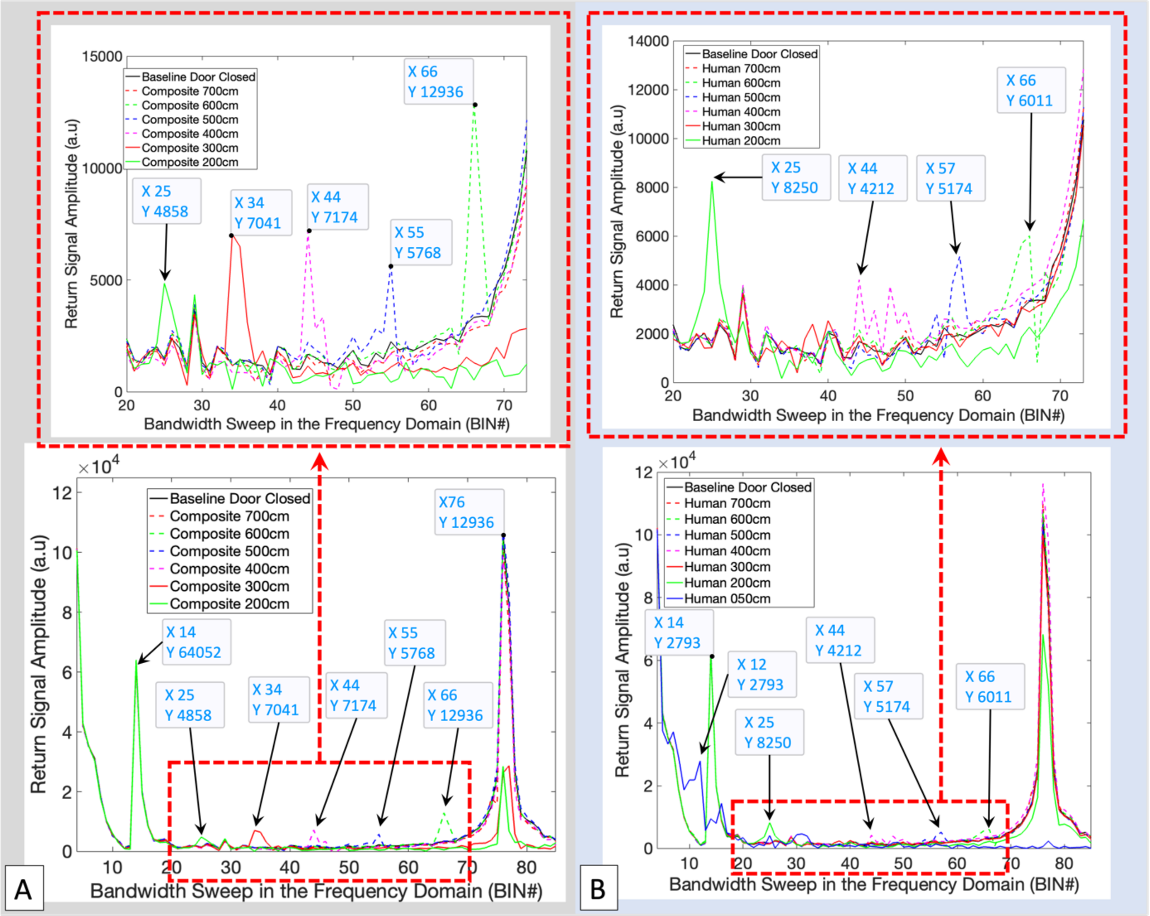


Figure 8-29 FMCW radar signal of material under test through the doorway where A showcases the results for the composite material and B displays results for the human [368]†.

8.4.2.1.3. Foresight Monitoring Summary

The FMCW radar sensor serves as an innovative payload that autonomous systems can employ to detect humans beyond direct line of sight or those concealed by infrastructure. For instance, in scenarios where a human enters a workspace through a closed doorway, the sensor enables a robot to proactively adjust safety standards through foresight sensing before the human enters the collaborative workspace.

In addition, under identical experimental conditions, a K-band radar operating within the frequency range of 24-25.5GHz was employed. However, it could only detect the presence of the metal sheet beyond the doorway within the entire 700cm range. The composite material and human, on the other hand, were detectable only up to a distance of 200cm (1m beyond the doorway). This limitation might stem from the higher frequency of the K-band radar, resulting in reduced penetrative power through materials explaining the inability to differentiate the composite material and human from the baseline measurements at distances exceeding 200cm [368]†.

The robust sensing capabilities of the FMCW radar also make it a valuable asset to complement primary navigational sensors in scenarios with opaque conditions such as smoke, steam, or mist. These conditions often compromise the accuracy of visual spectrum and laser-based navigational systems like cameras and LiDAR. Utilising FMCW radar sensing in such unforeseen circumstances supports navigation, ensuring mission resilience and safety compliance. This becomes particularly critical in situations where a robot needs to navigate to a designated area for easier recovery [368]†.

An emerging sensing technique, through-wall/through-door sensing, is poised to play a pivotal role in establishing trust and safety compliance for autonomous systems in the future. This capability allows the sensor to update path planning and safety rules proactively before entering a workspace, enhancing situational awareness.

8.4.2.2. Ground Integrity Inspection

Typically, many robots are designed to operate around consistent well-defined environments with flooring which is safe for their manoeuvrability. Whilst many robots are branded as all terrain vehicles, there is still some scenarios where robots can become stuck such as a Clearpath Warthog which is designed to navigate over snow, however, in summer months when conducting the same inspection mission became stuck in boggy terrain (as displayed in Figure 8-24) [447]. Therefore, the quality of the terrain is pivotal in achieving a successful mission. The motivation of this section includes using the FMCW Radar sensor previously discussed to identify areas of the terrain which the robotic platform should avoid ensuring a successful mission. This contributes to advancing sensing capabilities for optimised autonomous path planning [399]§.

Static Investigation

Firstly, the FMCW radar is setup in a controlled desktop setting to determine its capability in sensing liquid as presented in Figure 8-30. Subsequently, the FMCW radar system is affixed to a Clearpath Husky, and successful testing and validation occur in a realistic environment featuring areas with significant groundwater saturation. The effective amalgamation of FMCW radar with autonomous environmental characterisation and mapping holds the promise of introducing novel parameters for terrain integrity data, including the identification of water, snow, ice, oil, or other contaminants on the operating surface that could pose risks to UGV operations [399]§.

The results in Figure 8-31, display that FMCW radar sensing is sensitive for displaying the results of dry, damp and wet flooring within the static investigation. Secondly the radar was positioned onboard the manipulator arm of a Clearpath Husky and driven with the radar crossing over the control variables of dry zone, the test area with the variable under evaluation and returning to the dry zone. The test area with the control variable is the contrasting agent, such as dry, wet or damp area [399]§.

Figure 8-30 A) The test area was moistened using a wet cloth, and a slight surface sheen was observed as a result of the moisture. B) Approximately 20 milliliters of water were placed within the sensor's field of view [399]§.

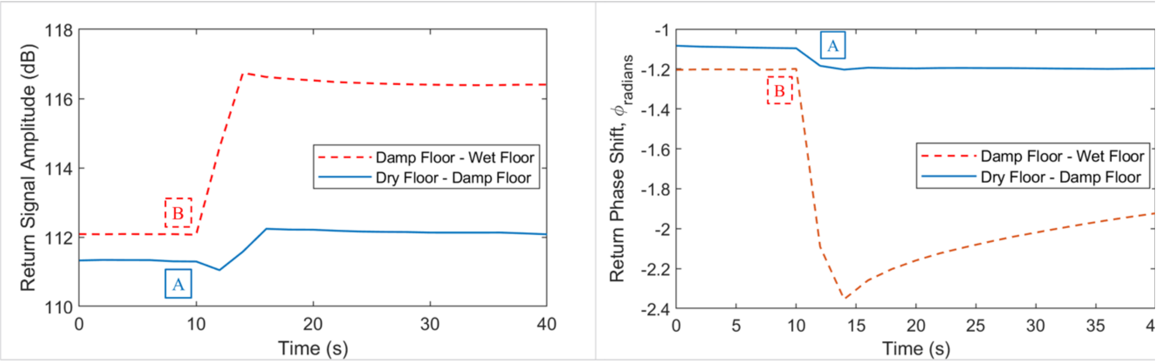


Figure 8-31 The static FMCW radar outcomes are depicted over time in relation to the intermediate frequency associated with the 12MHz concrete flooring within the frequency sweep where all surface properties occurred at time = 10secs. The left side illustrates the return signal amplitude, while the right side illustrates the return phase shift for both Experiment A and B [399]§.

Dynamic Investigation

The FMCW radar can be viewed installed onboard the Clearpath Husky robot where a PolyLactic Acid (PLA) enclosure was used to protect the antenna from the manipulator gripper. The tip of the antenna was positioned 30cm from the concrete flooring where the arm was used to position the antenna appropriately. The extent of the test area is indicated by the blue overlay and is bounded by tape markers on the concrete floor as displayed in Figure 8-32. The field of view of the sensor is indicated by the orange and yellow cone overlay and traverses an area where moisture was applied as a contrast agent and that is flanked by regions of dry concrete within the test area. Data was acquired under three surface moisture conditions:

1. Conducting a "dry" control scan involves the robot moving slowly over the dry test area, serving as a baseline dataset.
2. Perform a "damp" scan by maintaining the same test area boundaries and transit rate, but dampening the midpoint with a wet cloth.
3. Execute a "wet" scan with the entire test area saturated using approximately 100 ml of water.

In each instance, the movement of the Husky A200 is from point 1 to point 2, as indicated in Figure 8-32. Figure 8-33 shows the RSA response at an IF of 12 MHz for the three surface moisture conditions. This IF corresponds to a 30 cm height from the ground to the sensor tip. The legend in Figure 8-33 describes the sequence of target conditions, with each start and end point being dry. A key observation of these datasets shows, as in the static data, there is a direct relationship between RSA and water volume in the sensor FOV. The relationship between the surface moisture conditions for the return signal phase can be seen in Figure 8-33 (right graph), where clear responses are evident.

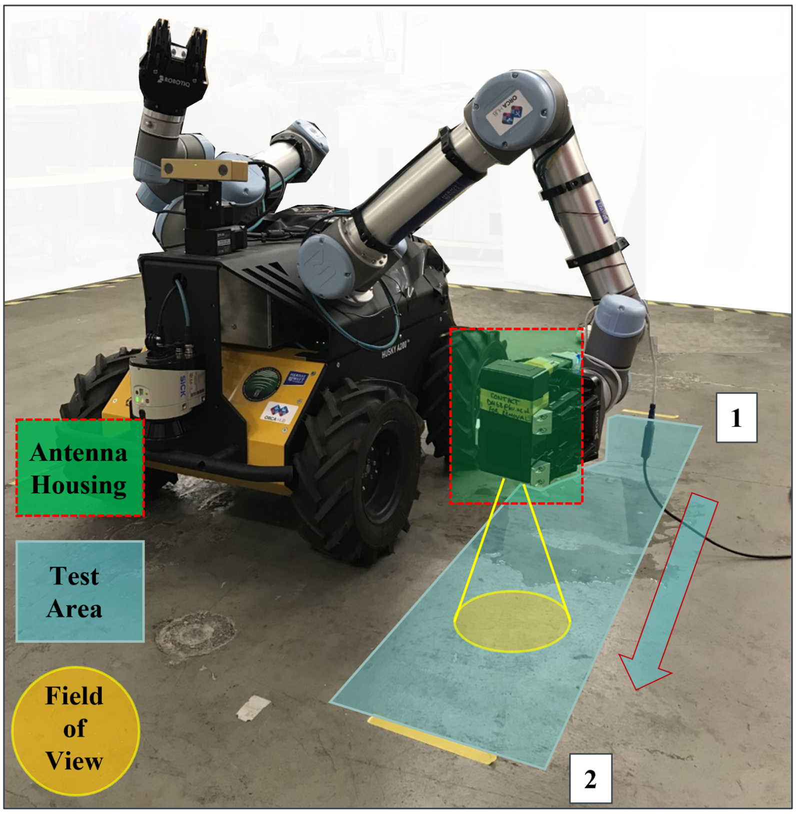


Figure 8-32 Experimental setup with an illustrative overlay showing the test area and sensor field of view. Sensor tip at 30 cm above ground, with points 1 and 2 indicating travel directions for data acquisition [399]§.

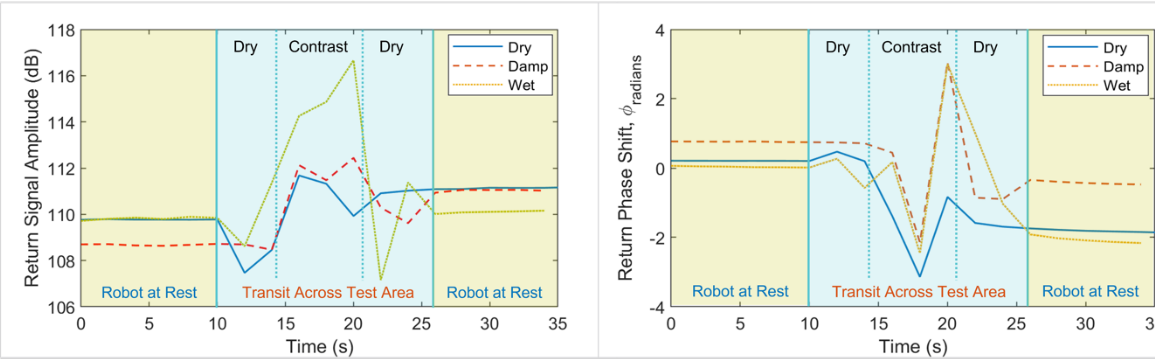


Figure 8-33 Dynamic microwave return signal for the investigation where the left displays the return signal amplitude and right displays the return phase shift where the blue segment matches and can be viewed in Figure 8-32 [399]§.

8.4.2.2.1. Summary

Static testing reveals the RSA sensitivity to water volume within the sensor's field of view, displaying consistent behaviour across the dry concrete baseline and varying degrees of water presence. This consistency extends to the phase shift, where an increased volume of water in the field of view results in an increased phase shift from a baseline. These static tests affirm the FMCW sensor's suitability as a fixed position sensor, enabling the detection of ground condition differences from a single sensor which does not require contact with the surface being inspected. Dynamic tests also highlight distinct signal contrasts in different moisture level scenarios, evident in both amplitude and phase responses. While the relationships identified in static testing remain consistent in dynamic data, this phase of testing emphasizes the need to adapt sensing parameters for improved data acquisition rates and signal variance. The benefits of enhanced data acquisition rates include facilitating real-time updates to costmaps through data averaging and thresholding algorithms, as seen in previous studies [361,448]. Additionally, higher data acquisition rates support faster UGV transit through the test area [399]§.

As discussed in [361], the sampling rate must exceed 1.0 Hz to enable the UGV to update its costmap, plan new paths, and initiate execution before committing to traversing undesirable areas. Interpolation in the costmap is necessary to incorporate FMCW observations into the robot's configuration space. However, fluctuations observed in dynamic testing may become spatially averaged out, potentially masking distinctions apparent in static tests. This could lead to challenges in reliably distinguishing between dry areas and those with minimal moisture when the robot is in motion. Despite this, FMCW proves to be a robust method for providing autonomous robotic systems with awareness of surface and subsurface ground integrity, establishing itself as a strong candidate for this purpose [399]§.

The FMCW radar sensor deployed in this research has a wide use of use cases where in future I expect that the sensor can be used as a single sensor for a wide range of these applications depending on the extensive use cases. To date this utilises a consistent methodology for laboratory-based investigations which will be scaled to real-world use case evaluation in the field to validate the effectiveness of the sensor.

9. Discussion

This thesis has examined the deployment of multi-robot fleets where many robots have been deployed within the ORE and nuclear sectors. Robotics and autonomous systems have significantly improved for a number of reasons due to direct investment within robotics and indirect investment in areas such as increasing offshore wind farms globally and also increasing safety/inspection in the nuclear sector. Therefore it is clear that the benefits of robotics are well defined to enable the required growth. It is also clear that robotic capability of platforms have advanced significantly as robotic companies have reployed their robots with improved capabilities such as Boston Dynamics SPOT quadruped, Anybotics Anymal quadruped, Tesla Genesis humanoid, DJI aerial vehicles. This has enabled hardware challenges to be less of an issue, leading to an importance in addressing software issues to ensure that robots can overcome challenges via autonomy. For example, a robot can complete objectives and overcome challenges when a human directly teleoperates the robot, however, fails when the system is fully autonomous and faces the same issues. This is a challenge which can be solved in the near term (5-10 years), alongside other challenges which are now discussed under key themes.

9.1. Industry and Government

9.1.1. Unified Robotic Integration Framework

Commercial-off-the-shelf systems are currently created by robotic systems manufacturers which are not platform agnostic and only work with their own branded equipment and software. A key bottleneck exists in creating a framework, and standards, which are accepting and can easily integrate robots as a fleet. Such standards would include details of methods of communications, programming languages and a collation of data aswell as cybersecurity protocols. As an example, consider Robotic Operating System (ROS), offering a cohesive structure for combining various components and overseeing robot operations. Nevertheless, several robot manufacturers require end users to incorporate ROS post-purchase which often requires employing their exclusive supplementary hardware and additional costs. This poses a difficulty when it comes to exchanging data and ensuring accessibility across diverse robotic platforms. To address this issue, there is a need to shift from a product-centric value proposition to the concept of providing autonomy as a service. This shift would enable a network of dispersed products to collaborate, oversee their surroundings and human interaction, and maintain the robustness of the entire fleet.

9.1.2. Standards for certification

Autonomy is enabling robots to learn and improve the way in which they conduct tasks. However, if a robot learns a flawed approach of the method to complete a task or incorrect model of the environment, this can become dangerous with potentially catastrophic consequences. Robots should have the ability to certify their own systems by collecting data as a platform executes the autonomous mission [335]. The data could then be certified by onboard systems to verify the safe state of the autonomous system. In addition, currently, robots are presumed safe for operation when bought new and deployed ‘out of the box’. They are utilised until a failure occurs on a component, system or software which renders them broken and requiring repair. This often limits the productivity of the asset. In addition, breakdowns result in postponed IMR and require careful attention from a human to conduct the maintenance. Therefore opportunities exist in allowing for continuous monitoring of the robots themselves to reduce risk from faulty components which can develop over time to extended the remaining useful life of the robot [20]†. This is especially important as more robots are trusted to operate BVLOS as this will lead to new challenges to face where human-in-the-loop operators will be required to ask the following questions. Does the problem exist in the cyber physical system such as an error in the digital dashboard or does the error exist in the physical robot deployed BVLOS? This would create further postponment in troubleshooting if self-certificiation is not implemented accuratley.

9.1.3. The Threat to Resilient Robotics in Hazardous Unstructured Environments

Resilient robotics is a key area which will require significant research and investment. Currently, service robots are programmed to complete missions in well controlled environments. However, significant work is required to ensure that robots can operate in the real world which is often a high consequence environment due to weather, terrain, personnel and other varying factors which a robot must overcome safely. This becomes especially important as many of the robots discussed in this thesis are required to access hazardous environments and confined spaces which may have communication or safety issues. Resilience is vital for these robots as it enables them to follow procedures to ensure they overcome different challenges where common dangers and challenges in navigation, sensing and locomotion occur. This could be via predetermined missions or as autonomy advances through its own learning from previous events. In attaining resilience, assistance from other robots within a fleet will be crucial to ensure a ‘stuck’ robot gets the perspective from a scenario. This could enable teamwork where one robot guides another robot out of a dangerous area.

9.1.4. Quantifying Resilience, Reliability and Productivity of a Robotic System

As robotic systems evolve, it will become crucial to measure the resilience, reliability and productivity of a multi-robot fleet. As pointed out by Hosseini *et al.*, there isn't a single universally accepted approach to evaluate resilience [449]. One potential method is the "number of nines," which gauges a system's resilience by quantifying the percentage of uptime in terms of how many nines are achieved (For example, 99.0% corresponds to two nines, while 99.999% corresponds to five nines). This methodology represents a future avenue for assessing the reliability of each robotic platform integrated within the SMuRF [20]†. With respect to productivity, this will likely be relative to the key performance indicators of the engineer managing the asset management around a facility. Therefore, this need will change depending on facility, environment, type of inspection and robots within a fleet.

9.2. Robotics Offshore

In future, the author expects that robotics and autonomous system deployments for the ORE sector will consist of resident robotics which remain (stored and charged) in the areas they conduct IMR activities. Resident cyber physical systems address bottlenecks in persistent safe autonomy, scalability and the orchestration of a fleet of robots[20]†. Some of the benefits of this approach include and are also displayed in Figure 9-1:

A. Increased awareness throughout an asset- Robots can multitask and can deploy multiple sensors at once. This means they can record data more efficiently. In addition, a resident robot can be deployed to conduct an investigation at any time regardless of weather conditions meaning it is more efficient.

B. Accelerated inspection- Costs and lengthy duration associated in logistics when transporting personnel are mitigated and robots can be deployed for a mission more quickly via a remote human operator.

C. Mission Logs- A storage centre of previous autonomous missions which can be used to inform future autonomous mission activities. It will be useful to assign key performance indicators to oversee what approaches to missions went well and what required improvements.

D. Reduced CO_2 emissions- Resident robots can utilise electrical power generated at the wind farm to mitigate the need for carbon intensive crew transfer vessels especially when transferring personnel offshore.

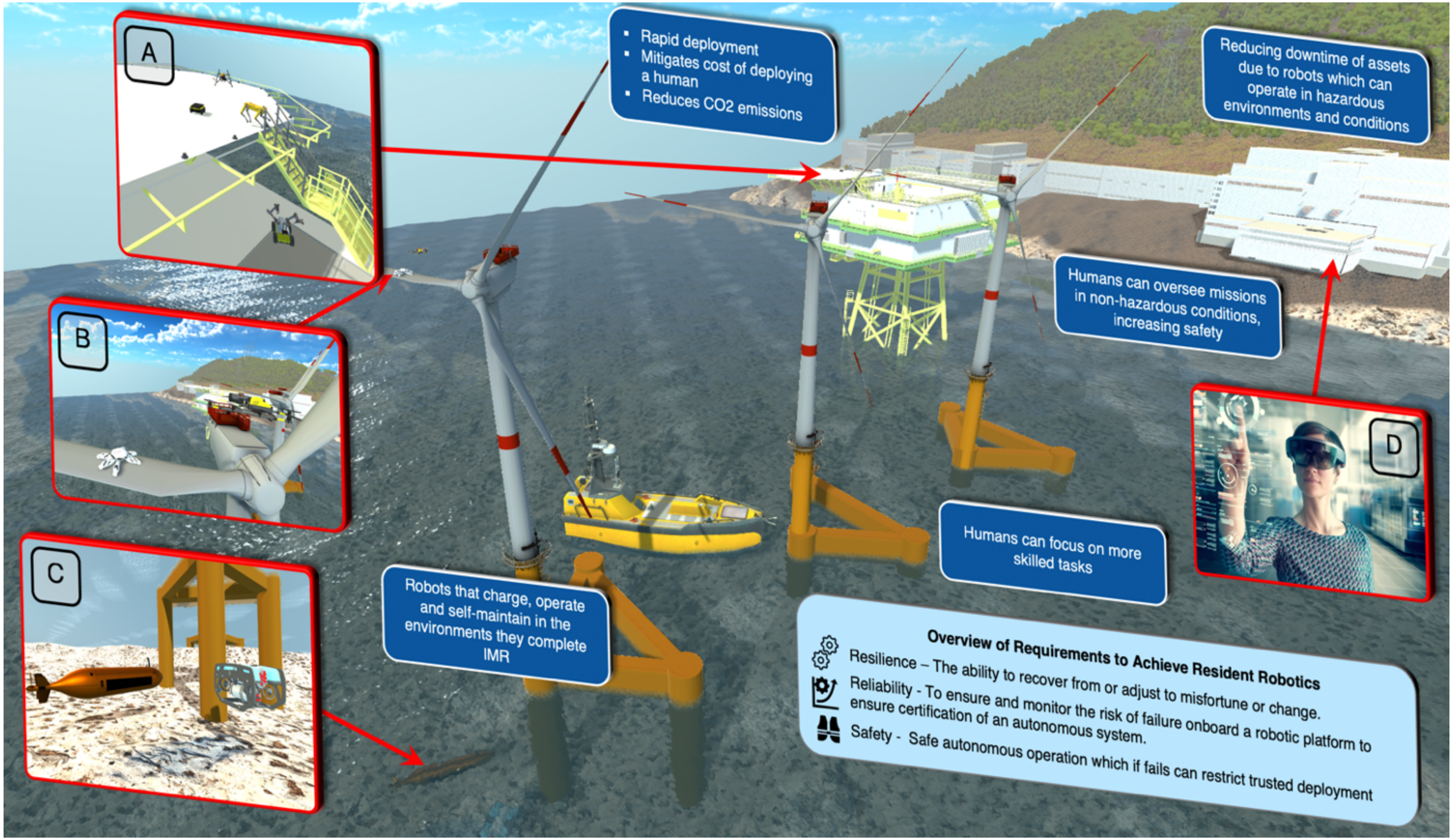


Figure 9-1 Future O&M via resident robots in offshore wind farms highlighting that a wide range of robotic platforms are used for the O&M of a site with a human-in-the-loop deployed at the shoreline. This requires a cyber physcal system and SMuRF for efficient oversight and operations [20]†.

9.3. Robotics in Nuclear

Robotics in nuclear, face similar opportunities and challenges in ensuring their success where key learnings can be shared across deployments with the ORE sector, in addition to the orchestration of similar robotic platforms within a fleet. At the time of writing this thesis it is perfectly timed to discuss that many of the robotic capabilities exist to be able to remotely inspect these types of facilities for ‘out of water’ activities. Robots have the ability to perform collision avoidance, overcome obstacles such as steps, inspect areas at height, take photos and complete other novel methods of anomaly detection via aerial vehicles, quadrupeds or wheeled robots. For maintenance and repair there are challenges which will need to be overcome in the next 5-10 years. Firstly, trusted manipulation from autonomous mobile robots deployed in the field will need to persistently occur. This will ensure that remedial action can take place in a timely manner when influencing the infrastructure in a facility. There are also challenges in communications where there are two options for the nuclear sector. The first option includes bypassing wireless communications challenges in infrastructure (wireless communications cannot pass through thick lead walls which are used to provide radiation shielding) where autonomy is relied on onboard the robotic platforms, therefore facility operators must trust that a robot can operate reliably BVLOS. *It should be noted that for the nuclear sector, this is not likely due to the requirement to oversee all new technologies and ensure fail-safe options via defence in depth.* The second and more likely option includes establishing cabled/wireless communication nodes to ensure supervision of robots. It is likely that in the long-term, robots will only remain supervised via direct connections due to safety concerns if a robot does experience a failure which could lead to catastrophic disaster. For sub-surface robots (underwater robots), there are key opportunities, as discussed previously, there are spent fuels ponds which have not been characterised in nearly a decade. Therefore, sub-surface robots will play a crucial role in calculating the amount of spent fuel currently in storage and the half-life of the spent fuel so that it can be appropriately disposed of. Both segments of robotics, whether underwater or above ground will inevitably require radiation hardening to ensure the safe operation of the robot. This may be via enhanced lead plating or new materials which are more lightweight to protect crucial electronics and sensors, alongside new methods to calculate the remaining useful life of a robot to ensure the robot does not become an operational hazard when it is deployed in a confined radioactive space. This is when failure layby zones may come in useful as discussed in subsection 7.2.3.3

Finally, whilst the physical architecture in terms of mobile robots and sensors in the field can and will exist in the future, a necessary step in the success of these deployments is the accessibility to data and information via a digital twin. This will enable for increased interaction and understanding for a HITL and for historical data to be visualised in an easier manner to rectify issues, run simulations to find effective outcomes of scenarios and also to evaluate methodologies which may not be appropriate too.

9.4. Robotics, Today, Tomorrow and the Future

There are several pathways being explored for robotics where Khalid *et. al* presents a pathway which includes a focus on system design, verification and validation, cost modelling and sensitivity analysis resulting in a reduction in levelized cost of energy. This pathway takes a ground-up perspective and presents different robot types [450]. Rinaldi *et. al* segment the route into traditional, physical, and digital technologies alongside connectivity where they provide an assessment in terms of a number of variables such as practicality, maturity, complexity and reliability, availability and maintainability. This was summarised under an energy digitalisation banner where their long-term vision is shared in terms of an almost fully automated asset management system [451]. With respect to the nuclear sector, a pathway is less defined with respect to multi-robot fleets whilst there is more of a focus in ensuring safe ground-up deployments of robots such as discussed by Tsitsimpelis *et. al* where the state-of-the-art is presented in robotics and mainly consists of robots being deployed to reduce man-hours spent under radiation and in a nuclear control room for inspection, surveillance, maintenance, repair and monitoring [132]. The pathway presented in this thesis is presented in Figure 9-2 and classified under short and long-term objectives.

Today: For ORE and nuclear sectors, robots typically operate whilst being directly operated by a human operator or within well defined autonomous missions, however, operate autonomously individually. Whilst this is a necessary step, robotic providers need to broaden this approach to become accepting that a wide range of robots will require to be used in the future and that a vital step is in connecting to a facility-operator’s chosen digital twin model to coordinate the robots. Therefore, robots need to break the cycle of only being operational under their own silos which includes hardware and software limitations.

Tomorrow: In the near term, robots will begin to be coordinated as a multi-robot fleet where a human can send commands for automated missions or conduct teleoperation missions of a robot fully remotely. This captures the advantages of robots more appropriately, as a human can intervene if necessary, giving them the command and control they require to oversee activities but still achieve the benefits of autonomy. Whilst these robots may still work within siloed missions, their information will be fed to a single digital twin for the human to better understand the information.

Future: Symbiotic Multi-Robot Fleets is a necessary goal when you take the perspective of robot coordination via a CPS. This is a long term goal as there are several elements which require to be built and include human-robot interaction, robot-robot interaction, trust, improved autonomy whilst achieving high processing to achieve this. Symbiosis would exist when robots are able to interact with each other to leverage the capability of the team leading to an improved mission completion. The robots will have the ability to identify these areas and request the availability of robots in the proximity to achieve this goal. This would be an iterative process as the robots learn what tasks are appropriate such as tool sharing, providing improved perspectives such as between UAV and ground robot or robot teamwork in multi robots with different payloads achieving sensor fusion.

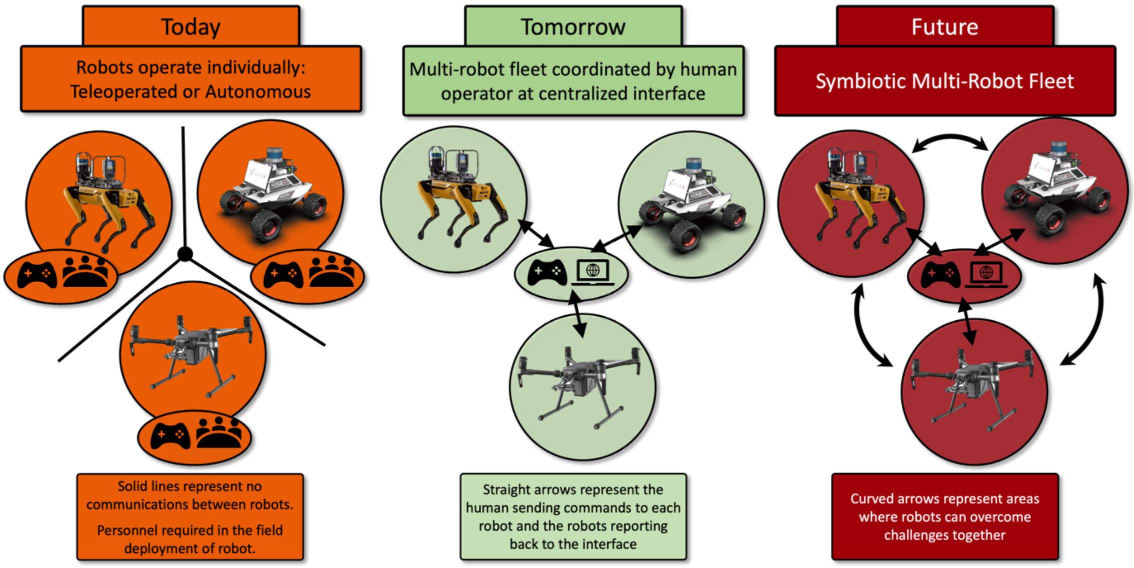


Figure 9-2 Pathway of optimised inspection via autonomy within robotic and autonomous systems.

9.5. Metaverse Applications

The Metaverse is transforming the way we interact with robots, sensors, environments, and humans, via the creation of a digital domain that is inter-operable, unified, and co-created by many collaborators. The metaverse unlocks opportunities that can benefit from dynamic, real-time and remote interaction across a host of different digital models and technologies [452]. This creates an ecosystem which is agnostic to digital technology, models and methods of interaction with the aim to enhance individual and collective human-team experiences [453,454]. Digital twins are a method currently in development within the robotics community which can be further enhanced by the metaverse [331]§.

In relation to robotics, the metaverse promotes opportunities to further develop the relationships which occur across humans, digital twins and robotic platforms. In an example where a facility exists in future where robots are used for O&M, the metaverse enhances the digital version of the real asset where a human can interact and view real data from the real asset and compare this with the digital version as shown in Figure 9-3 via the bidirectional arrows. This allows the human observer to ‘teleport’ to different areas of the digital plant seamlessly to view different areas with adaptability between a holistic and close-up view of the facility. The digital twin also allows for increases in productivity. Current procedures can be easily adapted to validate and verify different approaches to view for productivity, efficiency and safety improvements. This allows for these approaches to be verified ahead of running them onboard the real asset.

The connection of robots to the metaverse promotes agile systems and approaches, enabling smart nuclear, smart warehouses, novel medical applications and agile energy infrastructure. How each sector utilises the metaverse will differ in terms of lists of priorities. However, as robots and autonomous systems are iteratively introduced into current procedures, the key metrics will remain the same. These include the following:

Level of current capability- The ability of a system to complete a designed task such as inspection, maintenance or repair.
Type of deployment- Levels of autonomy from fully autonomous to teleoperation [20]†.
Metrics to gauge value- Validation of the value created for operators when handing over systems for operations can be measured in cost reductions, safety, resilience and productivity improvements.

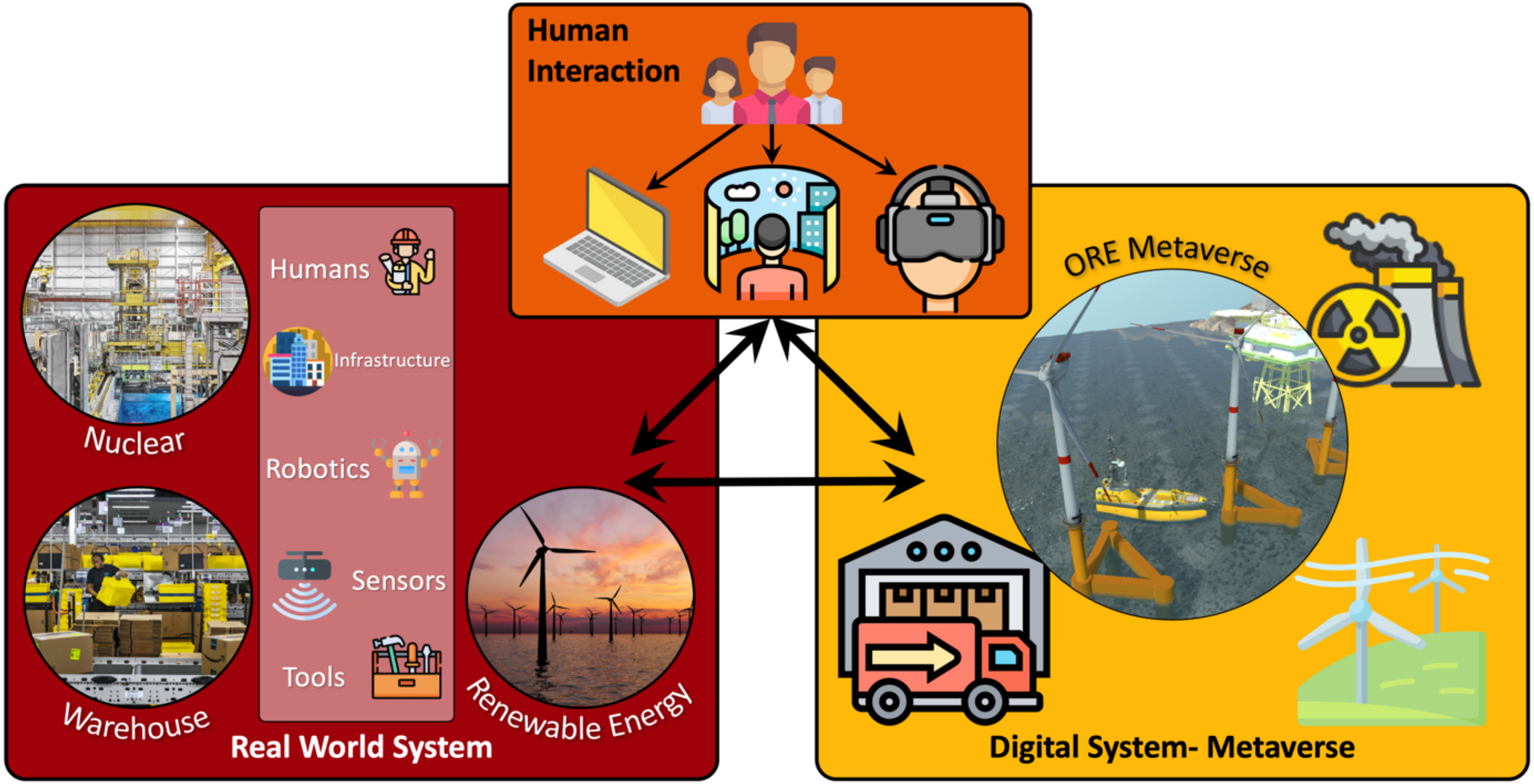


Figure 9-3 Key components which will benefit from Metaverse activities linked to CPS.

10. Conclusion

The aim of this thesis seeks to address a gap which exists in robotics and autonomous systems, where a system-based approach can address a potential identified bottleneck anticipated in the future. It has been identified that most research within the robotics sector is focussing on ground-up challenges to advance the state-of-the-art in the mechanical robotic capability and autonomy of robots whether this be decision-making, navigation or manipulation. These improvements are necessary to ensure persistent and trustworthy autonomy, however, focussing on these ground-up challenges limits the longevity of robotics as facility operators realise the potential, and scale up their deployment of autonomous operations. This necessitates a shift in research to address top-down challenges in the coordination of robots as they begin to resemble multi-robot fleets.

Chapter 1 identified the main motivation of robotics for the industrial sector; this included the necessary introductions to the context for both ORE and nuclear sectors, key market trends and challenges in current applications. These primary technical challenges involve a reprioritisation of approach via a top-down view and utilisation of a symbiotic approach to robotics.

Chapter 2 outlined the market trends that have led to the acceleration of robotics. This can be attributed to several other market trends which took place beforehand such as within the upscaling of the renewables sector and the O&M of the offshore and nuclear sectors. In addition, a survey of the academic database is presented via bibliometric analysis of robotics for both sectors and robotics identifying increasing trends for IMR robots due to an increase in publications related to cyber physical systems.

Chapter 3 presents the fundamental background reading required to understand the advanced concepts presented in this thesis. Cyber physical systems, safety, cybersecurity, standardisation and ground up versus top-down is presented. Key definitions including reliability and resilience are discussed which enables for improved understanding of the symbiotic solution presented next.

Chapter 4 includes a literature review of mobile robots and multi-robot fleets, where key conclusions include an overview of the levels of autonomy as many areas have not agreed on key definitions for autonomy. Within the state-of-the-art in field robotics, the DARPA

SubT challenge is presented where there were limitations across the teams in addressing multi-robot fleet operations. This included HITL cognitive overload in coordinating the robots and verification of segments of the inspections from the autonomous missions. Robotic teamwork was identified as an opportunity requiring improvement, as many robots operated independently and did not work as a team throughout the autonomous mission. Finally, communications in extreme environments were limited throughout the event and are identified as a future priority in autonomous operations.

Chapter 5 includes the design and discovery of the symbiotic methodology used within this thesis which is inspired from nature. Mutualism, commensalism and parasitism is presented, and these findings are then transferred to robotics and how they enable for the formation of robotic teamwork and opportunities in advancement of robotics. Finally, the hierarchal steps are outlined which enable for the scalable deployment of individual robots and multi-robot fleets.

Chapter 6 presents an overview and key properties of each robot used within this study. The information about actuators, sensors and other details are described in detail for each commercial off-the-shelf platform which was used. Each robot has different advantages and disadvantages in their contribution to the autonomous mission envelopes which follow in the next chapter.

Chapter 7 includes the key contributions undertaken in this research where the symbiotic approach is verified and validated via several complete autonomous missions within different environments and across different system levels in the symbiotic digital architecture. Of key importance is that this research utilised a cyber physical system which enables for other infrastructure, sensors and data to be fed into the digital environment alongside the key data from the SMuRF deployed in the robotic missions. In 7.1, a symbiotic system of systems approach is implemented for a single robot operating with multiple different systems. An autonomous inspection mission using the FMCW radar sensor to inspect for corrosion takes place where the autonomy onboard the robot self-certifies its own systems by ensuring they are operating as intended. The robot identifies these failures onboard via a run-time reliability ontology and then stops the mission when the robot is unable to ensure its safe operation. In 7.2 the symbiotic approach is applied to a multi-robot fleet presenting the first iteration of a Symbiotic Multi-Robot Fleet (SMuRF) once again applied to an offshore substation inspection use case. The HITL coordinates and oversees the robots from a digital interface where each robot has been chosen to complement the wide range of capabilities within the team. This enables for the leveraging of capabilities across the robot team to ensure for an efficient inspection mission to take place via quadruped, wheeled and aerial robots. In 7.3 the SMuRF is deployed once again, however for a nuclear use case where the key contributions address resilience, reliability and safety throughout the mission envelope via symbiotic interactions and query-based learning for the HITL. This aims to lead to autonomy as a service where the objectives of this work include improved digitalisation so that a remote operator can access real-time information from the SMuRF deployed within the facility in addition to symbiotic interactions across the robotic team, and FMCW radar sensing for ground integrity inspection to localise potential aqueous contamination and minimise further spread of contamination across a nuclear facility.

Chapter 8 presents the results from FMCW radar sensing where the sensor was used for asset integrity inspection for structural health monitoring and foresight monitoring. The microwave sensor provides previously inaccessible data into the integrity of surface and subsurface properties related to the characterisation of fault precursors for porous dielectric materials. The sensor is lightweight, non-contact and does not require a couplant, making it stand out from the current state-of-the-art. Foresight monitoring enables for non-visual threats which can detrimentally affect the mission profile of a robot. This work addressed human detection and through-door detection where the robot successfully detected and distinguished between a human and other materials. In addition to ground integrity inspection where the robot could detect if there was moisture on the ground. This would reduce the risk of spreading a potentially contaminated substance or becoming stuck in examples in future such as boggy terrain.

Chapter 9 presents the discussion where additional overarching findings from this thesis is presented where a unified robotic integration framework is discussed to enable robots from different vendors to establish ‘plug and play’ communication standards to become part of a robotic team. Secondly, certification standards are presented where currently robots are deployed as safe to use ‘upon purchase’ however, as robots are deployed more regularly, this will require several stages of certification throughout their lifecycle and to extend the remaining useful life of the assets. Resilience is also presented alongside challenges in how an operator can measure the productivity in a system to ensure it is efficient both in terms of task efficiency and economically for the facility. Finally, key opportunities for the ORE sector and nuclear sector in robotics is presented alongside near-term opportunities in robotics via a ‘today, tomorrow and future pathway for robotics’ which mostly revolves around the stages required to create a SMuRF and where symbiotic interactions can take place to create teamwork.

The deployment of symbiotic multi-robot fleet autonomy will reach a pinnacle via the successful integration of cyber physical systems featured centrally in quadrant 1 within Figure 10-1. This will require the successful integration and information shared across the requirements of the application (quadrant 2), cyber system (quadrant 3) and physical systems/capability (quadrant 4).

Quadrant 2 Application - For nuclear and ORE sectors, the application typically informs the research and development pathway in the state-of-the-art for both digitalisation and physical robots, hence the overlap in the Venn diagram in Figure 10-1. This requires key areas of information from engineering experience and the requirements which should follow within cyber and physical quadrants. Therefore, it is important that hazards are explained, the environment is described, and the type/challenges of IMR activities faced are evaluated. Key learnings in the application domain can inform on the actions, decisions and requirements for both cyber and physical segments where quadrants 5 and 6 display overlapping regions where informed information can help to advance the cyber physical system technology.

Quadrant 3 Cyber - The digital environment should enable the HITL to interact with the real world via interventions. This requires hardware such as keyboards, joysticks and VR headsets. However, there can also be a detrimental effect from information due to too much information where a human will experience cognitive overload and stress, therefore the cyber system design architecture should ensure this is considered. The cyber segment requires accurate models, visualisation tools and a feed of information to inform on current and future models.

Quadrant 4 Physical - The physical assets as mentioned previously can consist of fixed or mobile robots with a wide range of sensing payloads at their disposal. Depending on the communication bandwidths, elements of processing can be conducted at the edge where there is higher levels of processing available.

Quadrant 5, 6 and 7 Overlapping Regions – Gradually, moving centrally the overlapping regions are discussed. *Quadrant 5* facilitates the level of interaction and information between application and cyber regions. Questions such as what levels of interaction the engineers require, how can the cyber solution enable an intuitive task allocation and finally what is the best approach to ensure the digital twin model is realistic when compared to the real facility? Within *Quadrant 6,* the robotic engineers need to understand the requirement for levels of autonomy (reminder in Figure 4-1) of the robotic platforms; fully autonomous or semi-autonomous? However, this is informed by the risk levels in the facility, such as nuclear, where low risk approaches are mandatory and due to more stringent regulation than other sectors. Once the robot types are decided, the next objective is to ensure that the robot can access the area within the application. Therefore, deployment methods such as a resident robot or robot deployed remotely from shoreline or the requirement for a human to deploy the robot and be in the vicinity whilst the inspection occurs may be appropriate. Finally, the frequency of the use of robot to conduct the tasks relative to the regulation within the application needs to be considered. *Quadrant 7* includes the interactions which should bidirectionally take place across the robotic fleet and resident sensors to the HITL. This enables real-time decision making to take place via query-based learning where the human can intuitively investigate in a similar manner as they would in the physical site. This will require suitable bandwidth in communications with the physical assets.

The Venn diagram discussed in Figure 10-1 leads to opportunities in the cyber physical system domain where a human operator can access a wide range of information from a digitalised model and database. This approach is more efficient due to opportunities where cost reductions can be made via real-time monitoring, data-driven decision making, flexibility in systems and enhanced safety.

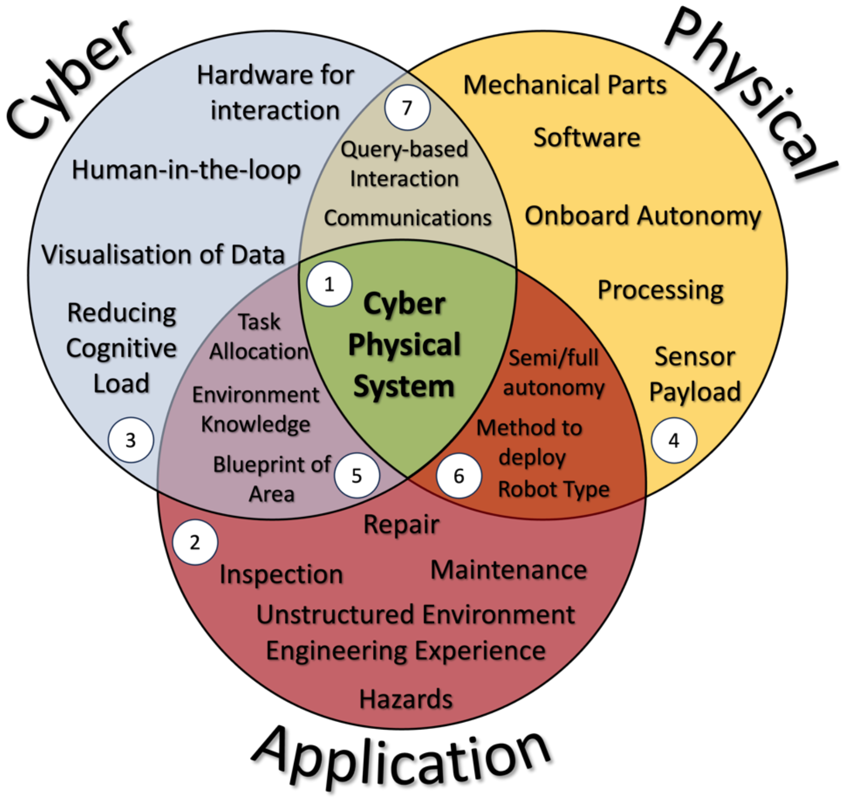
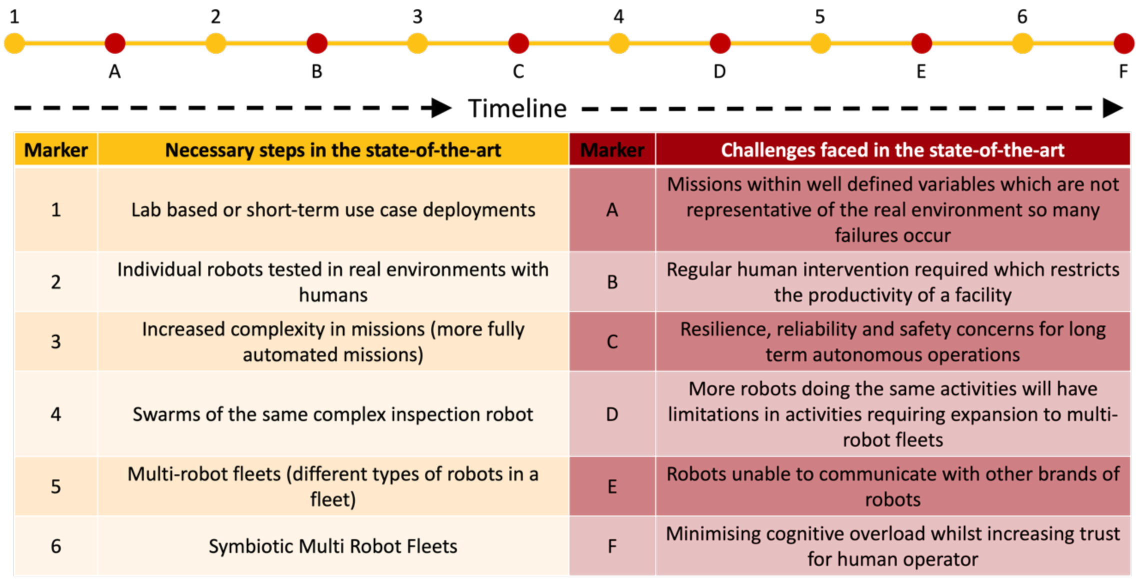


Figure 10-1 A summary of the requirements leading to an effective cyber physical system deployment highlighting areas in cyber, physical and applications for IMR mobile robots with numbered quadrants which are discussed in detail in the main text.

11. Future Work

This body of work has led to the design and development of a SMuRF, which will overcome many challenges within the industrial sector. However, this research has also led to new discoveries of challenges and opportunities. The future will continue in the field of symbiotic research where the author predicts that the following solutions and challenges will be faced in the regular deployment leading to a fully operational SMuRF as displayed in Figure 11-1. The state-of-the-art currently remains around positioned 1-2 where there are several lab based and individual robots in the field. However, these tests are limited to short term use case deployments. The timeline presents the necessary steps and then challenges which will be required to be overcome during each phase which namely feature resilience and safety challenges. As more robots are introduced within teams it will be vital that robots can coordinate the interactions required to act as a team. This can include the sharing of tools or shared carrying of larger objects such as when building structures.

In addition, to facilitate the pathway of this thesis, the technology sector will need to discover more advanced or clever communication methods to enable for the scaling of robotics. The challenge to overcome is that current methods often do not have the required low-latency or bandwidths to enable for a fully interactive, real time CPS. Areas such as 5G and 6G will enable rapid data sharing to CPS, however, this will require the advancement of infrastructure to ensure this across facilities and cities [455–457]. Whilst research will follow this trajectory, there are also opportunities which can be considered such as sending data at the right time or intermittent data sharing where data is only shared across the network at identified areas. This is a challenge which will be addressed as processing onboard autonomous systems improves as these challenges currently occur when high bandwidth is required for transfer of LiDAR data.



Marker	Necessary steps in the state-of-the-art	Marker	Challenges faced in the state-of-the-art
1	Lab based or short-term use case deployments	A	Missions within well defined variables which are not representative of the real environment so many failures occur
2	Individual robots tested in real environments with humans	B	Regular human intervention required which restricts the productivity of a facility
3	Increased complexity in missions (more fully automated missions)	C	Resilience, reliability and safety concerns for long term autonomous operations
4	Swarms of the same complex inspection robot	D	More robots doing the same activities will have limitations in activities requiring expansion to multi-robot fleets
5	Multi-robot fleets (different types of robots in a fleet)	E	Robots unable to communicate with other brands of robots
6	Symbiotic Multi Robot Fleets	F	Minimising cognitive overload whilst increasing trust for human operator

Figure 11-1 A series of short to long term objectives alonsgide the next respective challenges for the advancement of inspection robots in industrial facilities.

The industrial sector is incorporating robots alongside human engineers for inspections, allowing humans to concentrate on more intricate tasks and enhance productivity. While mobile robots can handle various inspection duties, challenges persist in applying them to accomplish more complex facility tasks, necessitating the involvement of human engineers. Difficulties also arise in the computer interfaces facilitating human-robot interactions in the field. For instance, teleoperation from a controller requires the human's undivided attention on the robot, limiting their ability to perform more complex tasks. Hence, the creation of a 'hands-free' interface is essential to boost productivity, enabling humans to focus on their tasks while a robot executes its objectives in a collaborative workspace. In addition, this can also be true for a human using a digital tool remotely where it may be difficult to teleoperate a robot remotely and complete the inspection task at the same time. Therefore, a ‘hands free’ method may enable for more intuitive multi-tasking. The discovery of Brain-Computer Interface (BCI) technology in deploying mobile robots within the industrial sector may be the solution to this challenge. In the approach, information from brain waves guides the robot's path, allowing a human to establish parameters and direct the autonomous robot to specific areas in the environment. Through a wireless transceiver, the robot follows the human's path, ensuring safe and efficient coordination with distance measurements [458,459]. The robot employs a camera or LiDAR for navigation and obstacle avoidance, operating autonomously but influenced in direction by the human thoughts. This technology implementation enables a 'hands-free' experience for humans, eliminating the need for teleoperation in human-robot interaction. This hands-free capability empowers individuals to concentrate on tasks, whether submitting information through tablets to a digital twin or using tools on-site, thereby optimizing productivity in collaborative workspaces. This would also have instrumental potential for people with disabilities in terms of operating their wheelchairs or prosthetics in the future [460–463].

12. Predictions

The aim of this section is to provide a set of predictions for robotics which may exist beyond the lifetime work of this author however, via this work, may be the pathway in the next 50-100 years. Whilst the predictions may seem fictional, a wide range of research activities could lead to potential opportunities in the future. For example, early personal computers were typified by the Apple I (invented in 1976) and IBM PC (invented in 1981), fast forward 48 years to 2024 and personal laptops with processing power many times greater than those early machines are accessible to nearly every person in the UK. The trends via computer hardware, software and processing will also lead to improved robotics, autonomous systems and CPS in the future.

Some major trends currently in both robotics and wider technology sector include the deployment of humanoid robots such as Tesla's *'Optimus Gen 2'*, Unitree *'H1 robot and G1 robot'*, Boston Dynamics *'Atlas'* and Agility Robotics *'Digit'* [464–468]. Robots to particularly note include the new electric version of the Atlas robot from Boston Dynamics where the company has a proven track record (Excellent capability and documentation) and whilst to date have not released the price of their new humanoid [467]. In contrast, Unitree recently released their G1 humanoid where prices start at $16,000 where any company will find it extremely difficult to match that price tag[468]. However, this will likely result in small amounts of documentation in developing the robot resulting in more challenges to initially overcome for researchers.

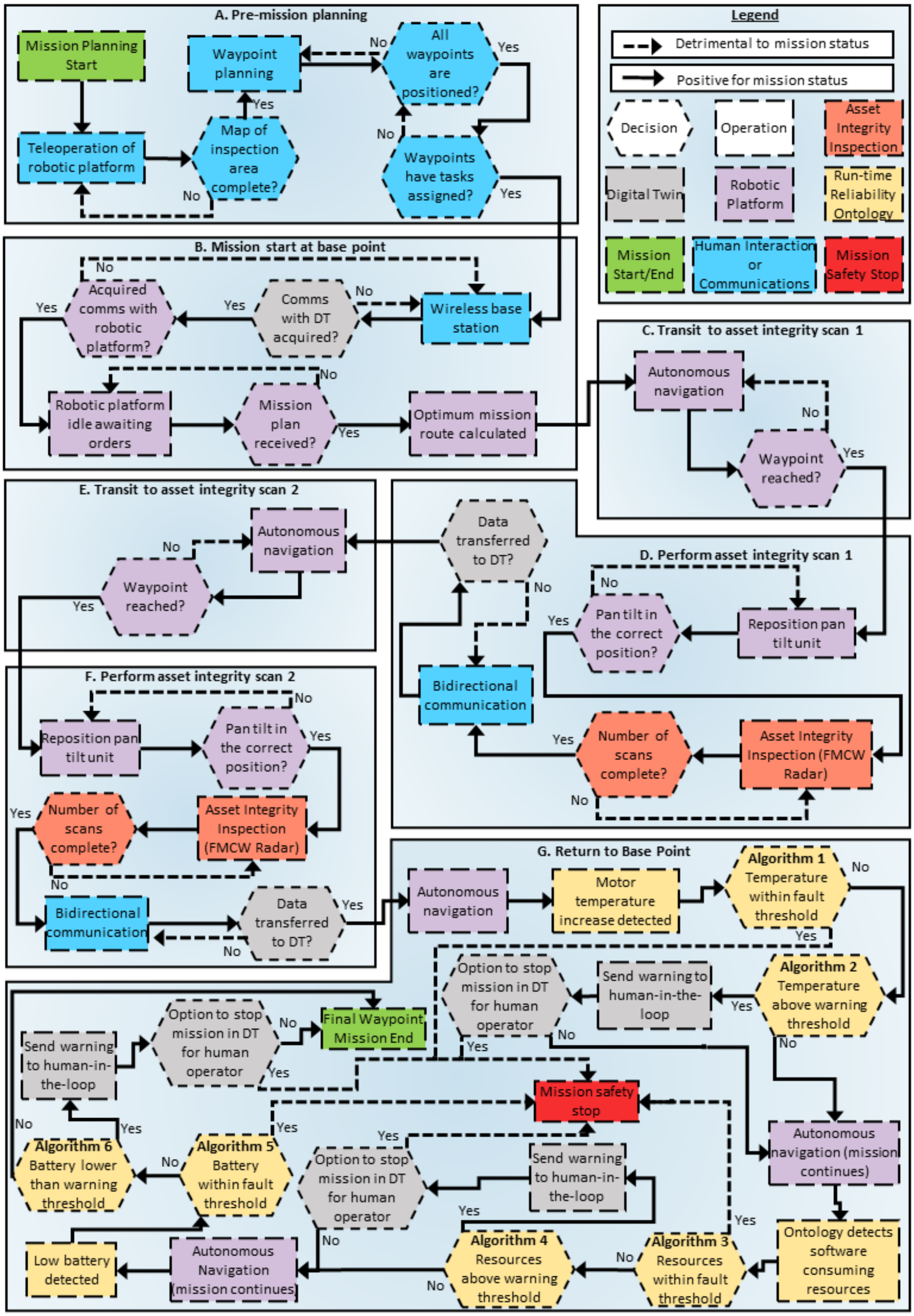
Whilst there will be many needs for humanoid robots, for the ORE and nuclear sectors, there is not necessarily a need for humanoid robots due to the requirements for access within confined spaces. Therefore, the author predicts that in 50-100 years we will see robots which are smaller, are more agile with smaller sensors onboard. Inevitably these robots will have improved battery percentages to enable for long term missions where robots may be able to operate longer than a human can. In addition, there will no doubt be speculation that there will be job losses for humans due to humanoid robots, however, it is expected that by 2030, 173,000 additional jobs will be required to ensure sufficient growth [469]. However, it should be noted that the role a human plays in the future will have changed by a large amount and that will require people to welcome changes and be prepared to retrain. An example may be where AI is used to inform on the role or task which a human is completing or when working alongside in a partnership with a robot where a robot can make suggestions in the most efficient way to complete a job.

For new infrastructure being commissioned in 50+ years, certainly there will have been more done to design these facilities with respect to how a robot would operate and maintain these facilities, therefore the author expects to see offshore facilities where robots are the 'first responders' to O&M as previously described in Figure 9-1. What is not visualized within that figure however, is the potential for the digitalization aspects where the full real-world infrastructure is exactly replicated in that of the digital environment. Autonomy within digital interfaces empowers the capability to examine historical data, determining optimal times for energy storage or transmission to the grid. It is complemented by self-generated insights into future energy costs, ensuring the production of sustainable and cost-effective energy. Simulations, incorporating diverse variables like the number of robots needed for offshore wind farm inspection, weather conditions, and sea states, facilitate the creation of these predictive models. Where these predictive models are trusted to be deployed ahead of human supervision provided within set safety standards.

Cybersecurity will play a vital role in all types of technology in the next 50 years. The potential from quantum computing could break existing encryption methods leading to new ways of securing sensitive information. This may lead to quantum-resistant research in encryption. As autonomous systems are trusted with inspection of larger assets, this will mean that robots will be collecting more information within databases and have the potential to cause catastrophic disruptions if hacked. Therefore, these systems will need to ensure that appropriate encryption is in place to prevent this.

13. Appendices

Appendix 13-1 The resulting decisions from the SSOSA during the autonomous mission envelope highlighting decisions, operations and system of system interactions [10]†.



Appendix 13-2 Written algorithms for fault and warning detection within the run-time reliability ontology [10]†.

Algorithm 1 Motor Temperature Fault Check

Require: Motor temperate does not exceed maximum threshold
Ensure: Motor temperature stays within safe boundaries

```
if temperature > maximum threshold value then
    mission stop
    notify user of mission end
end if
if temperature > critical threshold value then
    query operator if the mission should stop
    if input = yes
        mission stop
    else
        mission continues
    end if
end if
```

Algorithm 2 Motor Temperature Warning Check

Require: Notify user if the temperature enters a critical threshold
Ensure: Motor temperature stays within safe boundaries

```
if temperature > critical threshold value then
    query operator if the mission should stop
    if input = yes
        mission stop
    else
        mission continues
    end if
end if
```

Algorithm 3 Software Resource Fault Check

Require: System resources of the robotic platform do not exceed maximum threshold
Ensure: System resource usage of the robotic platform stays within safe boundaries

```
if process RAM usage % > maximum RAM usage % threshold value
or process CPU usage % > maximum CPU usage % threshold value then
    mission stop
    notify user of mission end
end if
```

Algorithm 4 Software Resource Warning Check

Require: Notify user if system resource usage enters a critical threshold
Ensure: System resource usage of the robotic platform stays within safe boundaries

```
if process RAM usage % > critical RAM usage % threshold value
or process CPU usage % > critical CPU usage % threshold value then
query operator if the mission should stop
    if input = yes
        mission stop
    else
```

```
            mission continues
        end if
    end if
```

Algorithm 5 Low Battery Level Fault Check

Require: Battery level does not reduce below critical threshold whilst in mission
Ensure: Mission stop before battery is completely drained

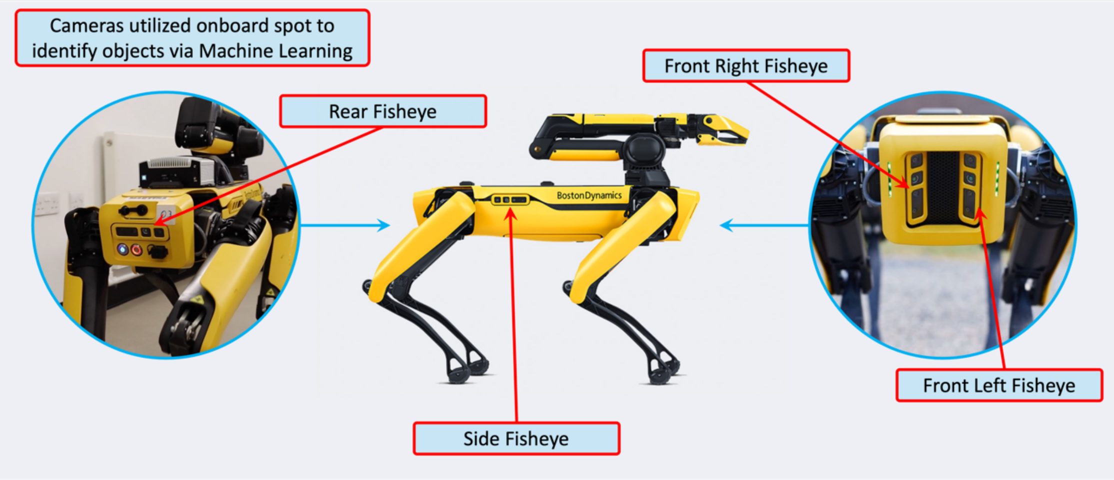
```
if battery SoC < critical threshold value then
    mission stop
    notify user of mission end
end if
```

Algorithm 6 Low Battery Level Warning Check

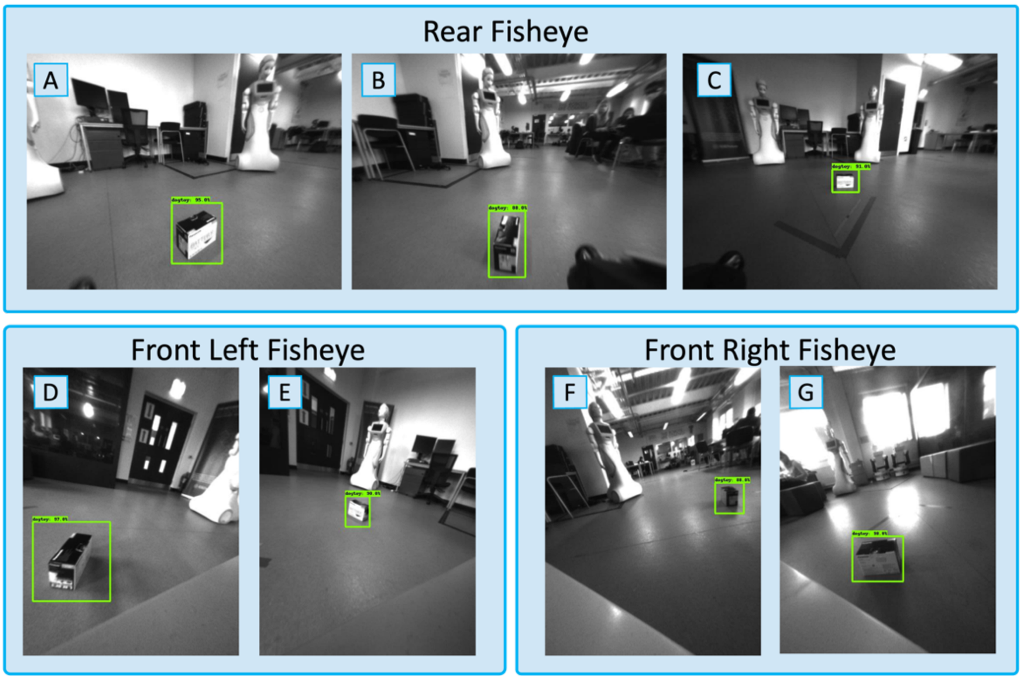
Require: Warn user of battery level entering warning threshold
Ensure: Mission stop before battery is completely drained

```
if battery SoC < warning threshold value then
    query operator if the mission should stop
    if input = yes
        mission stop
    else
        mission continues
    end if
end if
```

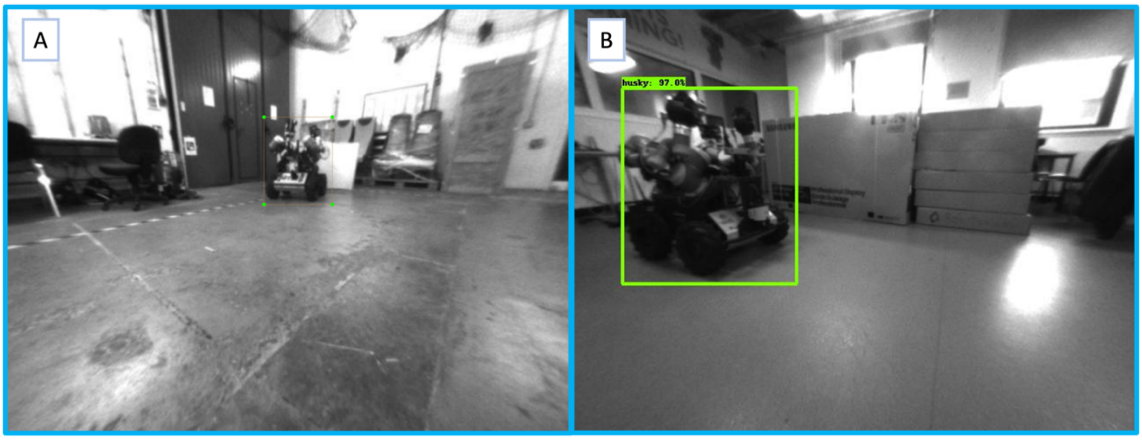
Appendix 13-3 positions of the fisheye cameras onboard the SPOT robot used for Machine Learning Segment



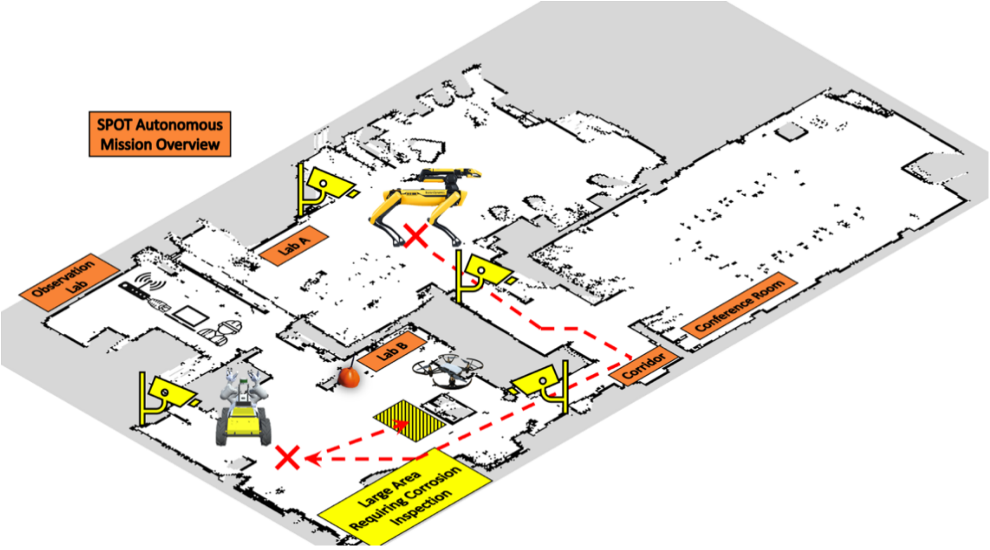
Appendix 13-4 Successful classification of the battery analogue using fisheye cameras resulting in different accuracies: [A] 95%, [B] 88%, [C] 91%, [D]97%, [E] 90%, [F] 88%, [G] 98%.



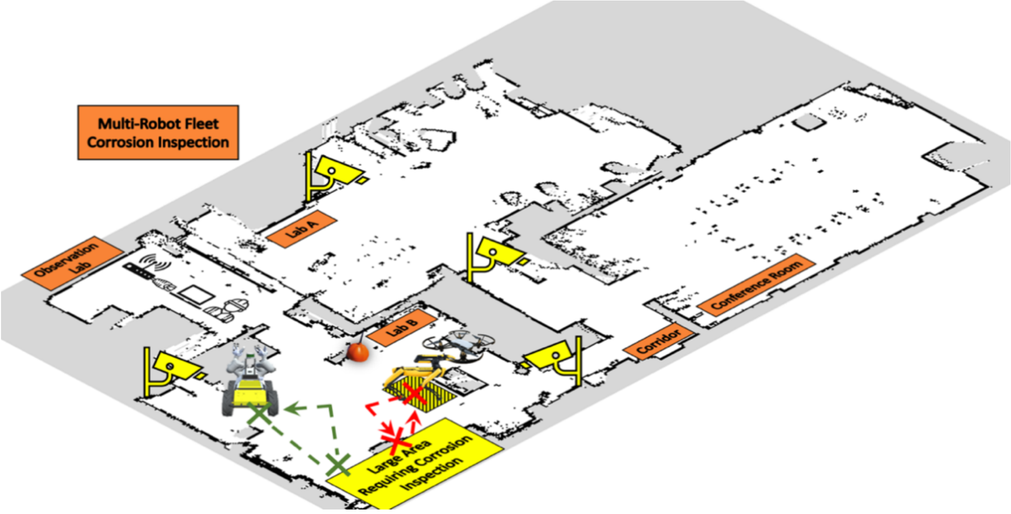
Appendix 13-5 Successful identification of the Husky robot via SPOT cameras. [A] Image captured from front camera onboard Spot during the live mission of the rear of Husky. [B] Image captured from front camera of Spot highlighting detection of the front side of Husky with 97% detection accuracy.



Appendix 13-6 MR Mission Route. Highlighting SPOT navigate all rooms route.

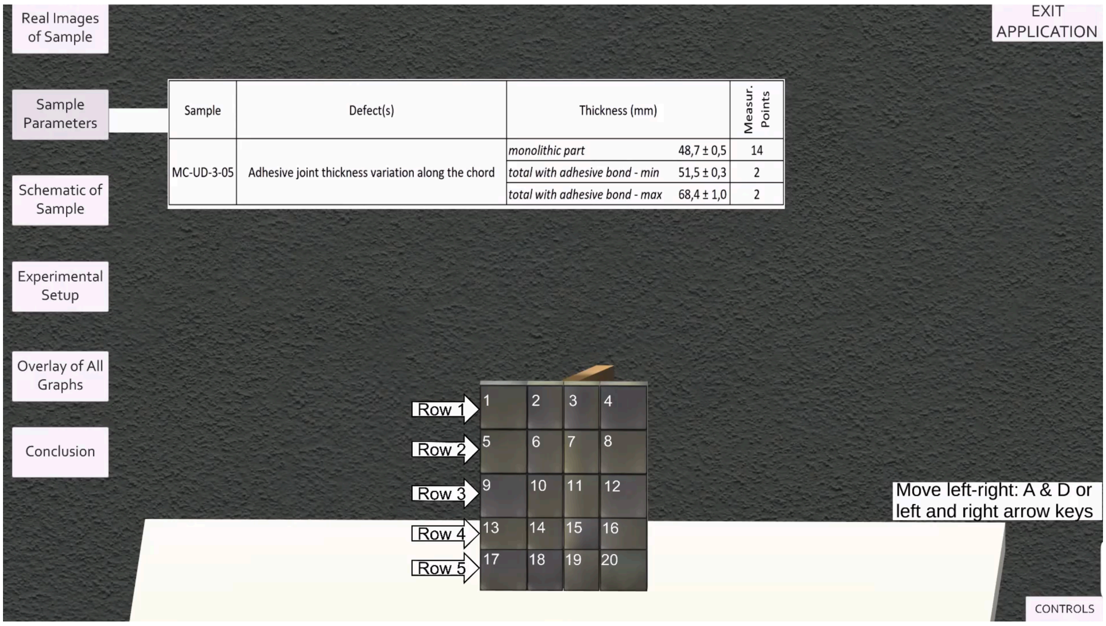


Appendix 13-7 MR Mission Route. Highlighting MR Inspection mission



Appendix 13-8 MR Mission Route. Highlighting SPOT battery retrieval mission.

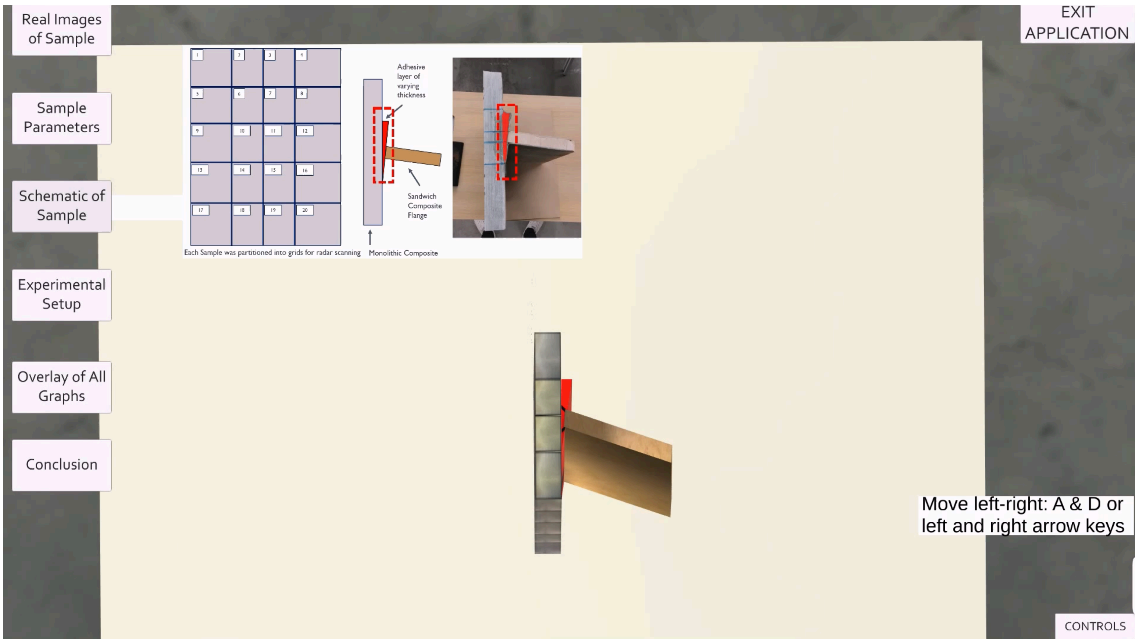
Appendix 13-9 Asset integrity dashboard displaying sample parameters [420]§.



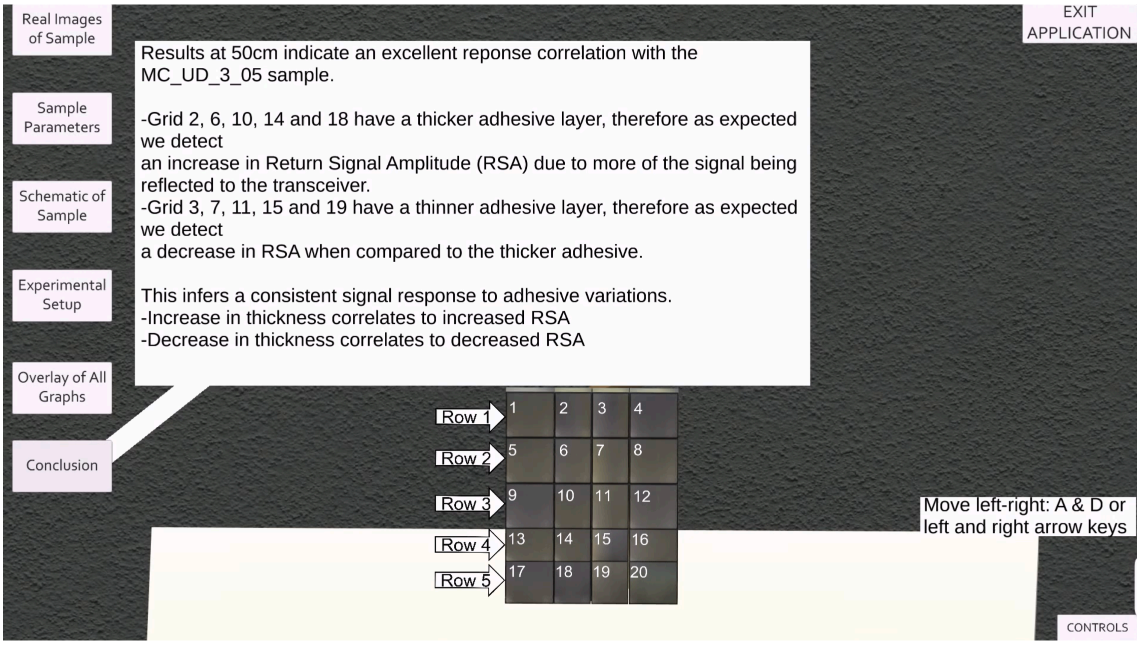
Sample	Defect(s)	Thickness (mm)		Measur. Points
MC-UD-3-05	Adhesive joint thickness variation along the chord	*monolithic part*	48,7 ± 0,5	14
		total with adhesive bond - min	51,5 ± 0,3	2
		total with adhesive bond - max	68,4 ± 1,0	2

Move left-right: A & D or left and right arrow keys

Appendix 13-10 Asset integrity dashboard displaying a schematic view of the sample [420]§.



Appendix 13-11 Asset integrity dashboard displaying the conclusions to the user [420]§.



Results at 50cm indicate an excellent reponse correlation with the MC_UD_3_05 sample.

-Grid 2, 6, 10, 14 and 18 have a thicker adhesive layer, therefore as expected we detect
an increase in Return Signal Amplitude (RSA) due to more of the signal being reflected to the transceiver.
-Grid 3, 7, 11, 15 and 19 have a thinner adhesive layer, therefore as expected we detect
a decrease in RSA when compared to the thicker adhesive.

This infers a consistent signal response to adhesive variations.
-Increase in thickness correlates to increased RSA
-Decrease in thickness correlates to decreased RSA

Appendix 13-12 Related Work within Foresight Monitoring: LiDAR and Through Wall Detection

Within this review of state-of-the-art technology, firstly, the identification of the limitations within LiDAR is presented through a laboratory-based experiment for BVLOS. Secondly, a literature review is conducted via IEEE Xplore on through-wall sensing methods. The aim of this literature review is to identify limitations in sensing mechanisms that robotic platforms regularly use and are unable to detect objects concealed or not within the immediate line of sight (within a neighbouring environment) [368]†.

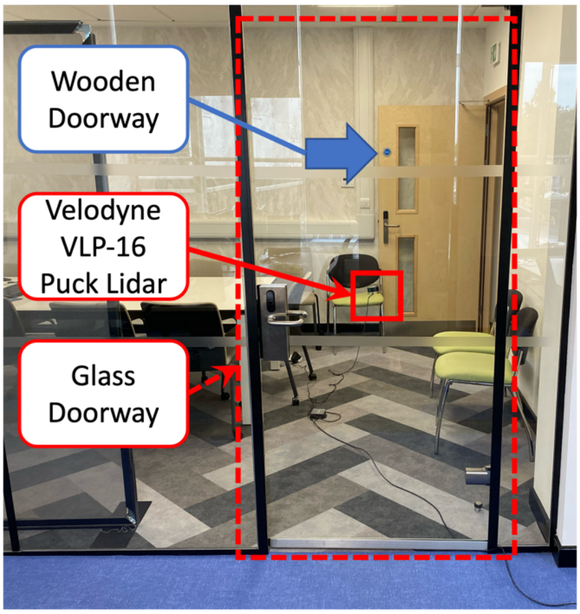


Figure 13-1 The VLP-16 Puck Velodyne LiDAR is placed on a chair, strategically positioned to maintain a direct visual line of sight with both the glass door (enclosed by the red dashed box) and a wooden doorway (indicated by the blue arrow) [368]†.

LiDAR serves as a fundamental and efficient sensor employed in Simultaneous Location and Mapping (SLAM) for Robotics and Autonomous Systems (RAS). Typically installed on ground or aerial vehicles, LiDAR sensors emit pulsed lasers in a 360-degree range, generating precise 3D maps of the robot's environment. This data is then input into SLAM, enabling the robot to employ collision avoidance for autonomous navigation within a given mission [368,470]†.

BVLOS commonly refers to a robot operating at a considerable distance from a human operator, often teleoperated via a camera without direct visual contact. In this context, BVLOS is defined as a robot possessing the capability to detect objects outside its immediate line of sight, such as beyond a closed doorway. The doorway can be represented as a transparent doorway (made of glass) or a solid door [368]†.

In the investigation, a VLP-16 Puck Velodyne LiDAR was employed and positioned in a room corner with a line of sight to two doorways: a glass doorway and a solid wood doorway, as illustrated in Figure 13-1. Various scenarios were devised to assess the limitations of LiDAR for both visual and BVLOS [368]†.

The conclusions drawn from Figure 13-2 are as follows:

A. In this scenario, the human is successfully detected as the glass door is open.

B. In the case where the glass door is closed, the human is detected. However, the LiDAR does not detect the glass door, indicating an undetected object that a robot could potentially collide against.
C. With the wooden doorway open, the human is detected along with the background of the corridor.
D. When the wooden door is closed, the human is not detected as they are not in the visual line of sight of the LiDAR. However, part of the corridor is detected due to the visual line of sight through a partition window on the door, highlighting a limitation in BVLOS safety compliance with a neighbouring workspace.

These scenarios reveal several limitations of LiDAR. The sensor cannot detect the presence of glass in the visual line of sight, posing a high risk to collision avoidance for robotic platforms. Additionally, the LiDAR is unable to detect the presence of objects or humans beyond the visual line of sight of doorways. These circumstances may lead to periods where safety standards are not met, as a robot may be unable to detect a human entering the workspace or accessing the doorway [368]†.

Sun *et al.* explored a through-the-wall sensing approach based on forward scattering to detect human presence. The study demonstrated positive sensitivity and low transmission power

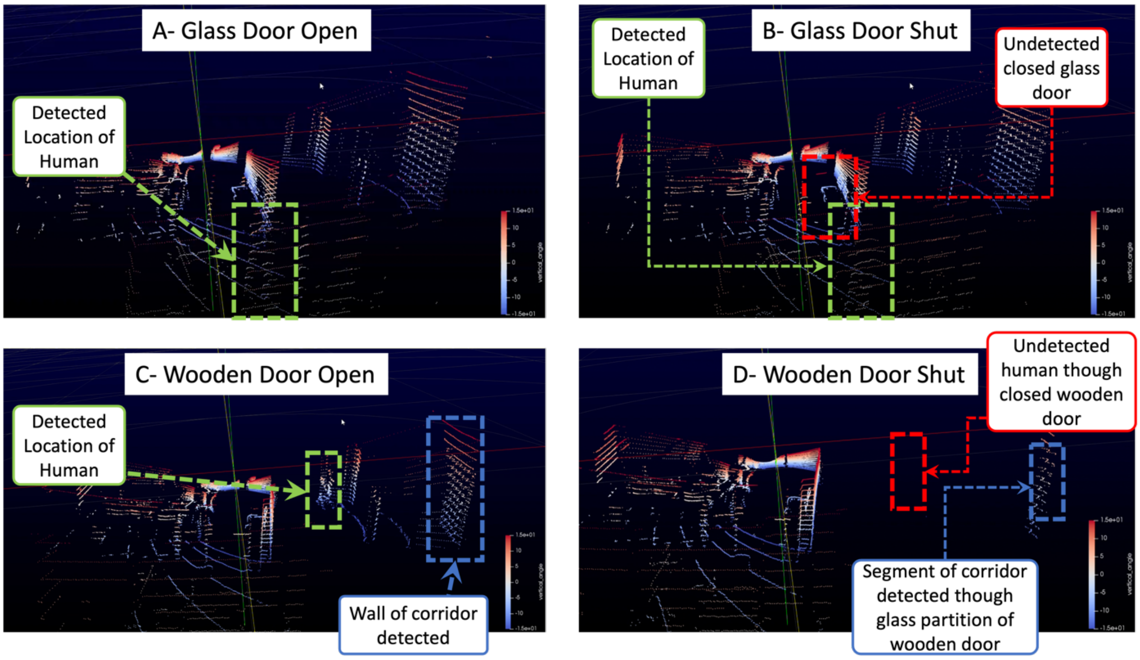


Figure 13-2 Several scenarios displaying results where LiDAR was utilised to detect the presence of a human for line of sight and BVLOS [368]†.

requirements for the transceiver radar, effectively detecting various human motions behind a wall [471]. However, this method's drawback is the need for two antennas (Tx and Rx) positioned behind each wall, limiting mobile field deployability.

Ma *et al.* introduced a corner multipath approach for through-wall radar imaging using compressive sensing. This method involves a linear array aperture with multiple wideband transceivers parallel to a wall, allowing detection of objects around the corner of the wall [472]. Limitations include the necessity for several antennas and the inability to detect signal contrasts for different material types, affecting target identification.

Alkus *et al.* employed a W-Band millimeter-wave FMCW radar with compressive sensing to illuminate a wall and target on the opposite side. While accurately localising a metallic object behind drywall, the graphical results require enhancement due to low image resolution, posing challenges in target identification [473]. The sensor also requires testing against thicker and denser wall types.

Yanik *et al.* discussed FMCW radar sensing in the W-band for identifying concealed items. The system demonstrated precise detection of concealed item shapes but required a complex setup with X and Y axis motors to construct the resulting image. Additionally, the sensor has not been tested for detecting items behind denser materials [474].

Table 13-1 summaries key properties of the aforementioned sensing methods, noting that many only require a single sensor (ideal for mobile robots) and can detect various objects through walls. However, a limitation arises as these methods cannot differentiate between human presence and other objects. The ability to make this distinction would enable a robot to update safety protocols before entering a new workspace. Moreover, none of the discussed sensors proposed a method to detect the range of objects BVLOS. This capability would be valuable for a robot to monitor safety compliance thresholds and update them as objects approach, mitigating safety risks [368]†.

Table 13-1 Characteristics and Limitations of Discussed Through-Wall Detection Sensors [368]†.

Reference	**Single Sensor**	**Object Detection**	**Detection of Human**	**Range Detection**
[471]	✓	✓	X	X

[472]	X	✓	X	X
[473]	✓	✓	X	X
[474]	✓	✓	X	X

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