Addressing Non-Intervention Challenges via Resilient Robotics utilizing a Digital Twin

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Abstract— Heterogeneous robot teams face challenges in reducing human interventions due to robot failure and environmental challenges in dangerous unstructured environments. It is therefore necessary to create a methodology to assess robot fleet failure rates to reduce the requirement for costly human intervention. A solution to this problem includes robots with the ability to work together symbiotically to overcome mission resilience challenges. However, robotic platforms generally lack built-in interconnectivity with other platforms from different vendors. This work aims to tackle this issue by enabling the functionality through a bidirectional digital twin. The twin enables the human operator to transmit and receive information to and from the heterogeneous multi-robot fleet. This digital twin considers autonomy for mission resilience and human-led decision making to enable the resilience of a multi-robot fleet. Decision-making within the digital twin triggers the symbiotic digital architecture to preserve mission continuity via adaptive planning in the robotic team. This creates the cooperation, corroboration, and collaboration of diverse robots to leverage the capability via a multi robot fleet, supporting the recovery of a failed robot. This research enables for robots to overcome resilience issues ahead of the requirement for human intervention.

Keywords—Cooperating robots, failure detection, multi-robot systems, wheeled robot, quadruped and recovery.

I. INTRODUCTION

Intervention offshore is dangerous and costly. If a robot fails offshore, humans are required to intervene by flying out to the robot and recovering it manually. In 2020, there were 11 major injuries in the offshore sector in the UK, with 47 further “over-7-day” injuries reported [1]. Human deployment via chartered helicopter is expensive and has resulted in fatal accidents in the past, reducing these flights has the potential for large cost savings [2]. Mission resilience for remote autonomous operations is an important factor in reducing human interventions in hazardous environments [3], [4]. We define resilience as the ability for an entity to adjust to or recover from misfortune. In terms of autonomous systems, this is the ability of a system to survive such events and still operate under adversity. Through this, mission resilience is achieved as the mission will still succeed. Digital Twin (DT) technologies enable resilience due to increased operational overviews of multi-robot fleet collaboration across resident robots, sensors and environment. This collaboration allows the fleet to meet common mission goals without the need for human intervention.

Currently, to ensure the safe deployment of robotics, humans are required to oversee and recover robots which have failed in hazardous areas, preventing robot loss. A key barrier in the deployment of fully autonomous robots includes autonomous systems which can meet safety compliance requirements. This would allow for imperative requirements where the robot can divert to a safe layby upon detection of a failure. This would allow for a human to safely recover the asset without being exposed to dangerous areas, e.g., confined spaces or nuclear sites. This would reduce necessary interventions, and when these interventions must still occur it ensures safety compliance. Using a Symbiotic Digital Architecture (SDA) will enable safe decisions to unforeseen issues and scenarios to mitigate risk [5].

This research proposes a DT to address non-intervention challenges which currently exist for autonomous platforms in the Offshore Renewable Energy (ORE) sector. This is enabled through automatic recovery of a failed robot. Decision-making within the DT can be used to trigger the SDA to preserve mission continuity via adaptive planning. These operations help to ensure mission resilience and minimise the need for human intervention. The DT maturity spectrum was published by the IET where this article focusses on level four to improve the two-way data..
integration and interaction via remote operations and control of the physical robotic asset from the digital interface. The key takeaway points of this article are listed:

1. The unique advantage of this DT includes the facilitation of symbiotic interactions across a multi-robot fleet to increase successful resilience of a team.
2. The implementation of a diverse robotic team with a DT, which all use diverse software architectures but operates synchronously to improve inspection missions.
3. Improved human-in-the-loop overview for the optimisation and coordination of a multi-robot-fleet with the aim to reduce in-person interventions.

To prove the viability of this system, Section I covers the state of the art. In Section II, the methodology of the architecture is explained and an example scenario for a multi-robot fleet operation is presented. This scenario involves a multi-robot asset integrity inspection mission using the Clearpath Husky, DJI Tello and Boston Dynamics Spot platforms. This scenario is then executed within an offshore analogue which represents an offshore substation, results are presented and discussed in Section IV. Finally, there is a conclusion of work done in Section V and future areas of research in Section VI. This work provides an example of the collaboration of off-the-shelf robots, the proof-of-concept video can be accessed at Mitchell et al. [6].

II. STATE OF THE ART

A limitation in most robotic platforms includes a design for single purpose missions or capabilities; there is not a single robotic platform suited to all tasks of inspection, maintenance, and Repair (IMR). Therefore, it is critical that several different platforms (multi-robot fleet) can communicate and interact with each other whilst sharing results to a DT. However, platforms from different vendors often have different operating systems and requirements. Some platforms, such as Clearpath Husky, use the open-source Robot Operating System (ROS), whereas others, such as Boston Dynamics Spot, have a closed system with a Software Development Kit (SDK) [7], [8]. In cases where the platforms have minimal built-in interconnectivity, they will usually only operate in robotic swarms with other platforms from the same vendor, requiring inter-device software frameworks to communicate [9]. One application of this can be in the form of a DT. DTs date back as far as the 1960s with the Apollo 13 mission and are a well-known concept within the state of the art [10]. Several types of DTs exist for manufacturing, robot, infrastructure and medical [11]–[14]. However, there are still challenges that exist in the path of more widespread DT usage. A challenge faced is the lack of standardization across systems. DT solutions currently on the market are bespoke systems made for specific sets of equipment or enterprises. There are no existing, observed, global standards for data formats, data transmission or connectivity concerning DTs. This creates challenges for interoperability – closed and separate systems cannot interact in a symbiotic manner. This poses yet further challenges with respect to digitalization, automation, and integration, which inhibits the development of DT technology and methodologies.

Challenges exist with marrying large numbers of assets with the processing power required to monitor the assets. There are solutions capable of processing data from many assets, but these require centralized data processing systems [11], [15]–[17]. Conversely, solutions that use low powered hardware are limited in the number of assets they can monitor [18], [19]. Therefore, the flexibility and scalability of hardware for monitoring assets and processing data is a major challenge currently facing DT implementations. Fig. 1 shows a summary of the knowledge gaps and opportunities raised in this article.

Our proposed Symbiotic System of Systems Approach (SSSOA) seeks to maximize the potential for autonomous mission success via increased resilience, reliability, and safety [5]. Symbiosis is the biological concept of multiple organisms which mutually benefit from their relationships [20], [21]. This stands in opposition to a parasitic relationship, where one organism gains benefit to the detriment of the other. In a symbiotic system, mutualism is achieved through the positive contribution to the health of assets, systems, and robots. This builds further upon safety, resilience, and reliability in dangerous offshore environments.

The SDA is designed to be a scalable, adaptable and platform agnostic architecture, which focusses on bidirectional communications to enable increased transparency in operational decision support. A benefit of this approach enables for autonomous systems and sensors of all programming languages.
etc. to be integrated and connected to the DT. This allows for the DT to be scaled up to include many systems via the cyber physical approach and is of interest with the perspective of robotic fleet management for facility operators [22]–[24]. This SDA has been developed primarily aimed at the needs of the ORE sector, but is designed to be flexible for multiple sector-wide use-case scenarios.

The SDA is displayed in Fig. 2 and represents the bidirectional knowledge exchange enabled by the architecture. This allows a human operator to make informed decisions, allowing them to access information about asset integrity inspection and a multi-robot fleet. Conversely, interacting with these processes and platforms through the DT allows the operator to share their knowledge with the robots, through insights gained from the hyper-enabled overview offered by the DT.

The asset integrity inspection block refers to Frequency Modulated Continuous Wave (FMCW) radar scanning of assets. FMCW scanning enables the detection of surface corrosion and subsurface defects within an industrial asset, such as a wind turbine blade or a structural component [25]–[27]. This is a useful method of preventative maintenance, as the non-destructive evaluation of these assets leads to early fault detection. Asset integrity inspection is a critical aspect of offshore operations and can be performed autonomously via robotic manipulators.

Mission resilience decision making is defined as the decisions made by the DT to ensure mission resilience. These can be acting upon fault and warning information to ensure another robot can continue the mission, or for performing safety stops to preserve the robots.

| Device             | Description                                                                 | Image                                           |
|--------------------|-----------------------------------------------------------------------------|-------------------------------------------------|
| Boston Dynamics    | Quadruped autonomous platform using a closed-box Python SDK equipped with an arm and six depth cameras. | ![Image](image1.png)                         |
| Spot               |                                                                              | ![Image](image2.png)                         |
| Clearpath Husky    | Wheeled autonomous platform using a ROS core equipped with LIDAR, SLAM, two manipulator arms with grippers and a depth camera. | ![Image](image3.png)                         |
| Dual UR-5          |                                                                              | ![Image](image4.png)                         |
| DJI Ryze Tello EDU | Off-the-shelf quadcopter UAV with downwards facing IR sensors for height measurement and a forward-facing camera for video only. | ![Image](image5.png)                         |
| Tello EDU          |                                                                              | ![Image](image6.png)                         |
| 2020 MacBook Air   | Laptop with 8GB RAM and Apple M1 chip.                                       | ![Image](image7.png)                         |

Table I. Devices and Technology Used in Mission Profile

Fig. 3. The ODSI, with numbers superimposed corresponding to features within the DT.
III. METHODOLOGY

The devices used in this demonstration are shown in Table I. Each robotic platform uses a different operating system and has different capabilities/attributes. This is to demonstrate a multi-robot fleet, where each robotic platform can apply its unique attributes to contribute to mission success via C³ governance (Cooperation, Collaboration and Corroboration).

The DT used in this mission is shown in Fig. 3, named the Operational Decision Support Interface (ODSI). It was developed using the Unity3D development package in C#. Unity enables rapid deployment to multiple devices, ensuring cross-platform compatibility, with alterations only required for the user interface to deal with different input methods. The ODSI acts as a control center for all robotic platforms, giving an immediate overview of the current activities of each platform. This is provided through a view of telemetry from each robot in the fleet and textual updates on mission status. The ODSI contains some decision making which enables symbiotic interactions across the required robotic platforms to complete the mission.

Fig. 3. is labeled as follows:
1. Status of Husky platform with buttons for pre-determined missions and a focus page.
2. Status of Tello platform with buttons for pre-determined missions and a focus page.
3. Status of Spot platform with buttons for pre-determined missions and a focus page.
4. Messages received from platforms.
5. Security camera footage with camera toggle.
6. Live video feed from Tello platform.
7. Button to trigger the multi-robot corrosion inspection mission (Fig. 6).

The focus page is demonstrated in Fig. 4 and is designed to give a more in-depth overview tailored to each robotic platform. The pictured example with the Husky shows the ability to position the arms with a “ghosting” interface, where the sliders control arm movement and the 3D model displaying the current (ghost) and desired (solid) arm positions. These features give the operator a hyper-enabled overview of the mission status, which is essential in Beyond Visual Line of Sight (BVLOS) operations. Corroboration between the data given by the ODSI and a visual overview of operations increases the operators trust in the system, so are necessary to include in the ODSI.

To demonstrate mission resilience, an ideal mission scenario alongside a deviation from the mission is presented within Fig. 5. To assess the resilience the second scenario mission is outlined in more detail as shown in Fig. 6 which also displays a deviation from the mission. The objective of this mission is to perform two asset integrity inspections of a corroded metal sheet...
and a wind turbine blade. These were chosen to mirror the types of asset integrity inspections completed in the ORE industry. In the validation and assessment of the resilience of the autonomous mission, the mission resilience decision making element is the focus of this investigation. This is achieved by running the mission twice, once in a “perfect” state where there are no issues (represented as solid lines), and once again with an induced failure to ensure mission resilience is achieved (represented as dashed lines). This fault is induced on the Husky robotic platform as a battery fault when the user requests manual repositioning of the arms. This allows the decision-making element to decide on which predetermined action to take. In the case that a warning is triggered, another robot will move to assist the stranded robot. The information is fed to a human-in-the-loop operator to draw on their expertise. To allow successful completion of the mission, the mission resilience decision making element alerts Spot to perform a battery replacement mission. This results in a mission deviation ensuring the resilience and recoverability of the Husky robot.

The cyber physical system layout of this mission is displayed in Fig. 7. This layout uses a client-server architecture, with a DT host laptop acting as the server of all communications, using a separate port for each platform. The Tello platform is limited as it can only use a direct Wi-Fi communication to the DT host laptop, therefore the host must be connected to a router via Ethernet to allow communications with all other platforms. Wi-Fi is used to connect to the Spot and Husky via the router. Cameras connected via USB act as security cameras giving different static viewpoints of the area for improved C3. For the purposes of demonstration, all connections are over a Local Area Network (LAN), future implementation work is to use the system over the internet.

For communication between each platform and the DT, TCP sockets are used. Messages are sent as short strings and decoded on each side as required. An example of this is shown in Fig. 8, where a mission can be triggered from a preset list using a single character string sent from the host DT. It also shows the typical format in which robot information is sent back to the DT, allowing data packets to be kept small in bandwidth constrained scenarios, which are likely when communicating with offshore platforms.

IV. RESULTS & DISCUSSION

This work represents a proof of concept for mitigating the risks that exist in reliability, resilience, and safety of autonomous robotic platforms. To demonstrate this, the missions were run as outlined in Fig. 6. The demonstration was performed in an offshore analogue space, as shown in Fig. 9.

The mission resilience decision making block (Fig. 2) was evaluated via this demonstration, where the actions of the multi-robot fleet were not hard coded in the sequence of events of the mission. The fault was induced on the Husky platform once the command to move the arms was sent, and the Husky informed the DT of this through a message. This information was shared with the DT and mission resilience decision making block. At this stage, the deviations of the mission occurred via a predetermined remedial action. In this case, the Spot performed...
an automated pick-and-place mission with the spare battery to enable resilience for Husky.

The “perfect” mission run-through showed the use case for an SDA via the cooperation of the robotic platforms to perform the asset integrity mission. This is shown visually in Fig. 10 using images from the security cameras.

The failure demonstration proved the use of an SDA for a DT. Corroboration was achieved in the Tello to establish a safe path to the layby. Collaboration was achieved through Spot providing the battery analogue to Husky. Cooperation was achieved through all robotic platforms sharing information to the DT. The reactions of the DT to the simulated robot failures enabled other robots to carry out tasks and ensure the resilience of the failed robot. In a real environment, this would enable the safe recovery of the robot from a hazardous area. The mission continuity afforded by the cooperation, corroboration and collaboration of the other platforms allowed the recovery mission to be carried out successfully without on-site human intervention. This is shown visually in Fig. 11 as viewed from the security cameras (B1 & C1) and photographs (B2 & C2).

In the deployment of a heterogeneous fleet offshore, there will be challenges in the maintenance of connection to wireless communications. This would require robots to store key data and share this information at different waypoints within a mission which have sufficient bandwidth and connection. Whilst this was not a focus of the investigation, in future, we may consider symbiotic interactions where a robot may share this information directly to another robot in a wireless communication denied environment where the other robots task is to locate wireless communications and share data to the DT. This could provide a solution where mesh networks are limited in deployment. A second challenge includes robots which are resilient to harsh operating conditions. This can include the ability to operate in fog, steam, smoke, mist and fire. This presents a challenge however, opportunities for symbiotic interactions where a different sensor package on another robot may help its team mate to navigate a difficult area. E.g. A thermal camera onboard one robot directing the route for a robot with a manipulator in an environment with a plume of smoke.

Multi-robot fleets will allow humans to focus on more complex tasks around a facility. However, this will inevitably result in shared workspaces where mobile robots operate around the presence of humans. Of vital importance in encouraging trust between RAS and humans includes the ability for RAS to operate within safe predefined limits, such as operating slower around humans etc. Therefore robots must be able to detect humans in proximity to the robot and operate according to safely defined limits. As robots learn to access more areas such as doorways, there are opportunities for through-wall detection where robots can update these safety regulations ahead of entering a shared workspace to ensure the safe deployment of robots in shared workspaces [28].

V. CONCLUSION

This work has presented a DT which enables bidirectional communications of a multi-robot fleet, increasing robotic resilience. This has been achieved via an SDA, which includes
a diverse range of robots and infrastructural sensors. The advantages of utilizing a multi-robot fleet include the leveraging of robotic capabilities to achieve a mutual goal: safe recovery of a robot, representing an advance in autonomous collaboration.

Of key importance is to ensure that multi-robot fleets do not become an operational risk for human intervention and recovery of assets. The development of fault detection and monitoring via a runtime reliability ontology represents an opportunity to address these non-intervention challenges, which inhibit BVLOS missions. Symbiotic digitalization enables for improved human-machine interactions across remote robotic agents. This leads to improved control and awareness for a human operator via increased resilience, reliability, and safety.

VI. FUTURE WORK

There is scope to add more complex planning domain definition language based planning to the SDA. Implementation work on this has been carried out by Carreno et al. on their work in extreme environments [29]. This would improve the dynamic robot planning, allowing for consideration of temporal aspects of planning and include situational awareness autonomously. However, its work is currently limited to simulation and has not been applied via implementation to physical service robots.

The manipulation of objects by robots needs to be improved to allow for true non-intervention and resilience. Currently, it is possible to use robotic manipulators as tools to pick and place objects, however it is not currently feasible for a mobile robot to perform maintenance operations on another mobile robot e.g., intervening internally on a robot and performing a battery replacement. Development in this field is critical for resident robotic operations BVLOS.

Using the system over the internet as a Wide Area Network (WAN) instead of a LAN will provide more opportunity for BVLOS operations, due to the possibility of fully remote operations, and will require full control over the network firewall and port forwarding settings. Such control strategies were outside the scope of this demonstration, as the focus was on displaying the benefits of a symbiotic multi-robot fleet.

Trust is also an issue relating to digital twins – how can an operator trust a BVLOS system without seeing it first-hand? It is vital that any simulations in a DT are based on realistic and correct models [30]. This helps to ensure that a DT will fully correlate to what is happening in the physical space. As such, trust is essential for decision making support, so standardization and progress in this area is essential for DT development [31].

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REFERENCES

[1] Health and Safety Executive, “Offshore Statistics and Regulatory Activity Report 2020,” Energy Division, Health and Safety Executive, 2020, [Online]. Available: https://www.hse.gov.uk/offshore/statistics/hr2020.pdf
[2] F. Menezes et al., “Optimizing Helicopter Transport of Oil Rig Crews at Petrobras,” Interfaces (Providencia), vol. 40, no. 5, pp. 408–416, 2010, [Online]. Available: http://www.jstor.org/stable/40931168
[3] 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.
[4] M. Shafiee, Z. Zhou, L. Mei, F. Dimmohammadi, J. Karama, and D. Flynn, “Unmanned Aerial Drones for Inspection of Offshore Wind Turbines: A Mission-Critical Failure Analysis,” Robotics, vol. 10, no. 1, 2021, doi: 10.3390/robotics10010026.
[5] D. Mitchell et al., “Symbiotic System of Systems Design for Safe and Resilient Autonomous Robotics in Offshore Wind Farms,” Oct. 2021, doi: 10.1109/ACCESS.2021.3117727.
[6] D. Mitchell et al., “ICRA 2023: A Scalable Cyber Physical Architecture for Symbiotic Multi-Robot Fleet Autonomy,” IEEE International Conference on Robotics and Automation , 2023. https://youtu.be/oypUrKbaM-c
[7] “Spot SDK – Spot 3.3.0 documentation.” https://dev.bostondynamics.com/ (accessed Jun. 09, 2023).
[8] “Robots/Husky - ROS Wiki.” http://wiki.ros.org/Robots/Husky (accessed Jun. 09, 2023).
[9] H. Hong, W. Kang, and S. Ha, “Software Development Framework for Cooperating Robots with High-level Mission Specification,” in 2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2020, pp. 11615–11622. doi: 10.1109/IROS45743.2020.9341328.
[10] S. Ferguson, “Apollo 13: The First Digital Twin,” Siemens, 2020.
[11] Y. Zhang, C. Zhang, J. Yan, C. Yang, and Z. Liu, “Rapid construction method of equipment model for discrete manufacturing digital twin workshop system,” Robot Comput Integr Manuf, vol. 75, p. 102309, Jun. 2022, doi: 10.1016/J.RCIM.2021.102309.
[12] P. Pereira et al., “Digital Twins in Built Environments: An Investigation of the Characteristics, Applications, and Challenges,” Buildings 2022, Vol. 12, Page 120, vol. 12, no. 2, p. 120, Jan. 2022, doi: 10.3390/BUILDINGS12020120.
[13] E. Pareit, P. Ardón, X. Liu, J. Lopes, H. Hastie, and K. S. Lohan, “A Digital Twin for Human-Robot Interaction,” ACM/IEEE International Conference on Human-Robot Interaction, 2019-March, p. 372, Mar. 2019, doi: 10.1109/HRI.2019.8673015.
[14] T. Mori, K. Ikeda, N. Tashikata, K. Teramura, and M. Ito, “Validation of a novel virtual reality simulation system with the focus on training for surgical dissection during laparoscopic sigmoid colectomy,” BMC Surg, vol. 22, no. 1, Dec. 2022, doi: 10.1186/S12893-021-01441-7.
[15] M. Armendia et al., “Machine Tool: From the Digital Twin to the Cyber-Physical Systems,” Twin-Control, pp. 3–21, 2019, doi: 10.1007/978-3-030-02203-7_1.
[16] S. Sierla, V. Kyriki, P. Aarnio, and V. Vyatkin, “Automatic assembly planning based on digital product descriptions,” Comput Ind, vol. 97, pp. 34–46, May 2018, doi: 10.1016/J.COMPIND.2018.01.013.
[17] K. T. Park et al., “Design and implementation of a digital twin application for a connected micro smart factory,” https://doi.org/10.1080/0951192X.2019.1599439, vol. 32, no. 6, pp. 596–614, Jun. 2019, doi: 10.1080/0951192X.2019.1599439.
[18] A. da S. Barbosa, F. P. Silva, L. R. D. S. Crestani, and R. B. Otto, “Virtual Assistant to Real Time Training on Industrial Environment,” Advances in Transdisciplinary Engineering, vol. 7, pp. 33–42, 2018, doi: 10.3233/978-1-61499-898-3-33.
[19] S. Rabah et al., “Towards improving the future of manufacturing through digital twin and augmented reality technologies,” Procedia Manuf, vol. 10, pp. 460–467, Jan. 2018, doi: 10.1016/J.PROMFG.2018.10.070.
[20] A. McConnell et al., “The Future Workplace: A Symbiotic System of Systems Environment,” Cyber-Physical Systems, pp. 259–329, Dec. 2021, doi: 10.1201/9781003186380-18.
[21] O. F. Zaki et al., “Self-Certification and Safety Compliance for Robotics Platforms,” Society of Petroleum Engineers (SPE), 2020, p. OTC-30840-MS, doi: 10.4043/30840-ms.
[22] R. Hoque et al., “Fleet-DAGger: Interactive Robot Fleet Learning with Scalable Human Supervision,” Jun. 2022, doi: 10.48550/arxiv.2206.14349.

[23] M. Wesselhöft, J. Hinckeldeyn, and J. Kreutzfeldt, “Controlling Fleets of Autonomous Mobile Robots with Reinforcement Learning: A Brief Survey,” Robotics, vol. 11, no. 5, 2022, doi: 10.3390/robotics11050085.

[24] M. Berndt, D. Krummacker, C. Fischer, and H. D. Schotten, “Centralized Robotic Fleet Coordination and Control,” in Mobile Communication - Technologies and Applications; 25th ITG-Symposium, 2021, pp. 1–8.

[25] D. Mitchell, J. Blanche, and D. Flynn, “An Evaluation of Millimeter-wave Radar Sensing for Civil Infrastructure,” in 2020 11th IEEE Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON), 2020, pp. 216–222. doi: 10.1109/IEMCON51383.2020.9284883.

[26] J. Blanche, D. Mitchell, R. Gupta, A. Tang, and D. Flynn, “Asset Integrity Monitoring of Wind Turbine Blades with Non-Destructive Radar Sensing,” in 2020 11th IEEE Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON), 2020, pp. 498–504. doi: 10.1109/IEMCON51383.2020.9284941.

[27] W. Tang, D. Mitchell, J. Blanche, R. Gupta, and D. Flynn, “Machine Learning Analysis of Non-Destructive Evaluation Data from Radar Inspection of Wind Turbine Blades,” in 2021 IEEE International Conference on Sensing, Diagnostics, Prognostics, and Control (SDPC), 2021, pp. 122–128. doi: 10.1109/SDPC52933.2021.9563264.

[28] D. Mitchell, J. Blanche, S. Harper, T. Lim, and D. Flynn, “Microwave Foresight Sensing for Safety Compliance in Autonomous Operations,” in IEEE International Conference on Omni Layer Intelligent Systems, 2023.

[29] Y. Carreno, J. Scharff Willners, Y. Petillot, and R. P. A. Petrick, “Situation-Aware Task Planning for Robust AUV Exploration in Extreme Environments”, Accessed: Jun. 09, 2023. [Online]. Available: https://bluerobotics.com/store/rov/bluerov2/

[30] K. Wärnfjord, R. Söderberg, B. Schleich, and H. Wang, “Digital Twin for Variation Management: A General Framework and Identification of Industrial Challenges Related to the Implementation,” Applied Sciences, vol. 10, no. 10, 2020, doi: 10.3390/app1010342.

[31] S. R. Atkinson, N. H. M. Caldwell, A. M. Maier, and P. J. Clarkson, “COLLABORATIVE TRUST NETWORKS IN ENGINEERING DESIGN ADAPTATION,” DS 68-7: Proceedings of the 18th International Conference on Engineering Design (ICED 11), Impacting Society through Engineering Design, Vol. 7: Human Behaviour in Design, Lyngby/Copenhagen, Denmark, 15.-19.08.2011, pp. 152–161, 2011, Accessed: Jun. 09, 2023. [Online]. Available: https://www.designsociety.org/publication/30671/COLLABORATIVE+TRUST+NETWORKS+IN+ENGINEERING+DESIGN+ADAPTATION