The Future Workplace: A Symbiotic System of Systems Environment

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Part V
Use cases of Solutions to Pandemic Challenges
The Future Workplace: A Symbiotic System of Systems Environment

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The United Kingdom (UK) generated 119.3TWh of renewable energy in 2019 an increase of 8.5% on 2018, meaning that 36.9% of the UK’s energy supply came from renewables. In the first quarter of 2020 alone, 47% of electricity generated came from renewables [1] and by 2050 the goal is for 100% of it to be from renewable sources. A recent analysis showed that the UK was placed to be able to deploy over 40GW of offshore wind generation by 2030 [2].

In the UK the predominant mode of production of renewable energy is through wind, both from onshore and Offshore wind farms [3]. However, the UK still relies on oil, gas and nuclear power to fully sustain its electrical demands [4]. The entire energy sector still requires humans to aid in energy generation, whether this is operating machinery on an Oil Rig in the North Sea, and monitoring systems in a control room for an Offshore Turbine or nuclear power plant.

Humans are typically required for performing inspection and monitoring operations as well as interventions when required. These jobs are considered to be located in extreme environments such as areas of extreme weather [5], potential Hydrogen Sulphide build up [6, 7] and high-pressure equipment blowouts [8] to name but a few. All these issues and dangers still exist but there is now the COVID-19 pandemic to also consider.

All regions of the world have been affected by the COVID-19 pandemic, the main transmission of the virus appears to be airborne and while maintaining one’s safety is possible outside the risk is considerably greater when the environment is enclosed/confined [9]. Offices and factories have proven ideal breeding grounds for COVID-19 outbreaks [10, 11] showing the chance of the virus spreading indoors an increase in comparison to outdoors and this even extends to multiple floors and entire

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buildings dependent on the air conditioning systems used. For this reason, the vast majority of countries affected by the pandemic are either in or have used one form or another of lockdown [12].

Lockdowns or stay at home regulations require workers where possible to as the name suggests to stay at home and work from there, this limits the possibility of viral spread and has reduced the overall CO$_2$ emissions [13] however the amount of power used domestically has increased [14].

The question is how can these new dangers of a pandemic and the past dangers of the extreme environments be mitigated using cyber-physical systems? A Symbiotic System of Systems Approach (SSOSA) via bidirectional communications can ensure the knowledge transfer across system elements to enhance the connectivity between robotics, infrastructure, and environmental systems.

2. Trends in Industrial Asset Management

As industry can be asset-heavy, the implementation of asset management can be viewed as an essential part of the effectual and efficient operation of an industrial organization. These asset-heavy industries can encounter over-capacity and low investment returns, therefore it is crucial for these organizations to implement a management system that allows for a continual life cycle, optimal operation and general equipment effectiveness through a complete asset management strategy [15]. It is necessary to identify what assets an organization has and to monitor and regularly inspect their current condition in order to effectively maintain them [16].

The term industrial asset management is used to describe any systematic process that maintains an asset throughout its lifecycle, through continuous planning and controlling, with the aim of maximising the reliability, lifetime, safety and value of assets whilst minimising costs [17].

Asset management is implemented through strategic policies that not only maintain assets but includes any actions that are required following any form of failure. These policies should align with the objectives and asset purpose of an organization, to achieve a steady operation to meet these objectives whilst maintaining a desired level of quality [18].

An established, optimized asset management strategy should be a detailed and thorough overview of an organization’s assets with consideration to any existing management objectives and performance targets. It should include a detailed risk management directory outlining current asset conditions with any historical and predicted deterioration and mechanical failures. Additionally, it should account for all financial and resources capabilities as well as constraints.

The International Organizations for Standardization (ISO) have produced an overview of asset management along with asset management systems. These standards identify common asset management procedures that are applicable for implementation across a broad range of organizations, asset types and cultures [19].

Asset management ought to consist of some defined key principles and attributes to be successful [19].

- Primarily, the asset management approach should be holistic rather than compartmentalized and identify risks with their associated costs and/or benefits (risk-based).
Additionally, it should be systematic and be a repeatable, consistent, and methodical approach (systematic).

- And it should establish the ideal value of performance and cost over an assets life cycle (optimal).

- It should also consider how the asset may change and thus perform in the future to guarantee that there is sufficient provision made for any future requirements of the asset (sustainable).

- Whilst recognizing that, to ensure success that the combination of attributes and all interdependencies are vital to this success (integrated).

For these principles to be successfully implemented there are a few essential aspects that should be considered. The organization should have good leadership and be working with a clear direction. The staff should be competent, have cross-functional coordination and commitment to the systematic process of asset management.

The ISO of asset management further explains that asset management required a coherent direction from management and actioning and implementation by knowledgeable and experienced employees. The ISO of asset management explains that lead management should show evidence of how they plan and commit to the execution and development of the organization’s asset management structure and how they will continually improve its effectiveness. This involves selecting people responsible for the assets and the asset system to ensure that it delivers all the outlined requirements of the asset management policies objectives and strategies.

If a there is no articulated direction and outlined priorities, then the management of assets becomes very difficult and it is at risk of becoming inefficient and ineffective, which wastes resources, time, and money. Therefore, the ISO have outlined several enablers that are important for effective asset management and have a substantial impact on the efficiency and effectiveness on an asset management system. These enablers are described as: (i) structure, authority and responsibilities; (ii) outsourcing of asset management activities; (iii) training, awareness and competence; (iv) communication, participation and consultation; (v) asset management system documentation; (vi) information management; (vii) risk management; (viii) legal and other requirements; (ix) management of change [19]. It is evident that these enablers and key principles require and rely on continual human involvement and actions.

The global, ongoing, COVID-19 (coronavirus) pandemic was declared as a Public Health Emergency of International concern, by the World Health Organization (WHO) in January 2020. Later in March 2020, it was declared as a global pandemic. Prevention methods were put into place by each country’s government to reduce the spread of the virus and to bring some level of overall protection to the population. These prevention methods included the wearing of facemasks, avoiding going out in public, social distancing as well as being advised to work (remotely) from home as a replacement for going to your place of work.

The COVID-19 pandemic, when it occurred, was an unexpected and unprecedented situation. Throughout the world, companies and organizations had to adapt and conform to the new restrictions and repercussions that came with the situation, which brought unique challenges with it. One of these challenges was managing their assets, as with employees working from home it is difficult to remain in control and consistent with the company’s assets.

The challenges that occur with people working remotely are, largely, due to two different concerns. One being that with company employees requiring equipment to
work at home, then a company can find it difficult to keep, literal track of their assets due to an increase in employee use of company devices. As to where these assets, such as laptops or software licences, are and who is operating them and in what capacity which can lead to assets being lost or becoming unaccounted for. Secondly, with employees not being able to frequently, if at all, work on site at a company there is increased risk linked with an absence of systematic asset management being conducted due to the necessity for human involvement. Consequently, the global pandemic has, further, pushed companies and organizations to reassess how they implement their asset management systems and how their employees can work effectively whilst working remotely [20–22].

Therefore, despite these standardizations and guidelines several industrial organizations have not optimized the operations and performances of their assets, especially in situations of exceptional and unanticipated circumstances [23, 24]. Industrial organizations can be challenged with insufficient and inaccurate maintenance procedures and money loss or interruptions to production due to unplanned outages and downtimes. Therefore, industrial processes are presently undergoing a digital transformation which is creating with it a new generation of intelligent, automated asset management solutions.

The world is continually making technological advances which can often mean that industrial companies can find themselves without a mature asset management strategy, due to insufficient data, which inevitably can lead to several challenges. However, these technological advances intelligence have also provided large amounts of asset data which has proven beneficial to asset management [25].

Industry 4.0, frequently designated the fourth industrial revolution or the Internet of Things (IoT), and was first developed in 2011 with the aim of maximising the productivity and efficiency in industry. The overall concept of Industry 4.0 is to connect the physical and virtual world together to solve various issues and problems in industry [26]. This is achieved using the internet and with the application of cyber-physical systems in an industrial production to achieve the Internet of services and the internet of things (IoT) [27]. IoT allows health monitoring of assets in real-time through automated data collection, which is analysed by algorithms for predictive maintenance (PdM).

Two other methods of maintenance are preventive and reactive, where the asset monitoring is conducted as cycle based or a run-to-failure respectively. One of the most effective ways to avoid failure of an asset is to plan for regular maintenance to reduce the risk of the asset’s failure probability increasing. However, the probability of failure that is associated with the age of the asset, only accounts for a small percentage of total assets owned by an organization. Furthermore, the remaining percentage of the assets will fail at irregular and random intervals. This makes preventive maintenance an inappropriate approach for this particular group of assets as it is likely that they could deteriorate and/or fail between the times scheduled for maintenance. In addition to this, reactive maintenance can be costly for critical assets as this will involve the interruption of production and thus there will be a lost revenue associated with this.

Historically, the application of predictive maintenance was fragile and expensive, as it involved the creation of custom programming software which allowed several systems to interface with each other to obtain data and deliver reports or warnings. However, any changes in this integration could cause the application to break.
Industrial Internet of Things (IIoT) platforms have made the development and support of predictive maintenance simpler.

As industrial markets are asset-intensive it is evident why asset management, reactive and predictive, and the general optimization of assets is significant to industries such as oil, gas, and manufacturing. Therefore, a particular priority of Industry 4.0 is the optimization of the management and tracking of assets. Further, Asset Performance Management (APM) 4.0 enables organizations to go beyond merely understanding their asset structure but to develop their asset usage in a much more comprehensive way. The main technological enablers of Intelligent Asset Management (IAM) are cloud computing, Internet of things, big data management and cyber security. IAM systems combines asset management with digitization to provide effective and optimized asset management through exceptional knowledge exchanges and management [28].

Asset management can be significantly enhanced through the development of digital technologies, e.g. Artificial Intelligence (AI) and Digital Twins (DT). As we have seen, data is crucial to effective asset management. This data can be classified into two different categories, reference and operational data which can be explained as data that informs us about everything concerning asset components, functioning and its configuration and data that can provide a real-time status, environmental data and maintenance history respectively. The combination of these data sets is referred to as a DT. Through a combination of these digital technologies, it is possible to conduct predictive or prescriptive maintenance and to link current asset management systems with those for process control.

An organization that has an IoT network are able to use smart assets that can transmit real-time data on the current condition of an asset to a central control centre, from which the key performance indicators (KPIs) can be calculated from the gathered data through the use of machine learning algorithms and AI. This automated data analysis can identify any trends and irregularities in the data to optimize and prioritize a schedule of required maintenance [29].

It was discussed earlier that maintenance practices can be separated into different categories, namely, preventive, conditional and reactive. Through the IoT, two further categories have evolved, predictive and prescriptive maintenance strategies. Prescriptive maintenance is a multi-variate model that utilizes various equipment and process data to identify and resolve or repair an issue, which is especially valuable in diagnostic situations where advanced or specialized knowledge or skills are required. Predictive maintenance that utilizes machine learning or individual algorithms specific to pieces of equipment for automated and multivariate data collection, this can be particularly useful in situations where a critical asset will encounter unexpected downtime which can have a substantial impact on an organization.

Sensorization is the terminology used to describe the use and integration of numerous sensors on a machine or device. Sensors are an effective and economical method for measuring and monitoring various variables such as temperature and vibration, therefore, sensors can enable equipment to detect any issues through an automated process.

The implementation of Industry 4.0 can be achieved, in part, through sensorization. However, before this can occur it is necessary for any existing operations to be digitized to allow for real-time detection of faults and problems. Real-time monitoring allows for immediate action should a fault or problem occur, eliminating any delays
which can prove to be costly to an organization. Additionally, real-time monitoring produces a data bank of useful and informative information regarding an asset that can in turn be used to optimize its operations.

Currently, asset monitoring is heavily human dependent. Sensorization removes the requirement of human monitoring which can, on occasions, lead to improper practice or insufficient detailing. By removing human reliance from asset monitoring this can allow for resources to be used in other critical areas as well as permitting, as mentioned, auto-detection of issues and the following required actions.

Due to the dangerous nature of the environment that requires sensorization, Robotics and Autonomous Systems (RAS) are becoming the go to method for sensor placement. They are not only being used for placing sensors but for independent inspection, monitoring and maintenance of any area required. The predominant use of robotics in the offshore sector has been in the form of Remote Operated Vehicles (ROVs) [30] and Autonomous Underwater Vehicles (AUVs) [31]. A comprehensive review of the recent developments in robotics for the Oil and Gas (O&G) sector has been published by Bogue [32].

These inspection methods can only be used periodically as they are expensive to deploy as all require trained operators and ships to launch from. Although providing essential information, they do not offer any form of real-time monitoring.

The potential for fire or explosion on any offshore platforms can be considered one of the most dangerous scenarios [33], and for this reason, any potential robot that has to operate in this area, would need to adhere to the ATEX directive 2014/34/EU in the European Union, the DSEAR in Britain or obtain IECEx certification for outside the EU and USA regions. A method of mitigating the danger of electronic ignition is to remove the electronics and replace them with an integrated fluidic logic circuit [34]. Fluidic logic circuits are at fundamental stage of research and have therefore not been deployed in the field to fully test them but have seen a recent uptick in research development [35–38].

A trend in the field of robotics is the increased integration or entire migration away from hard rigid robotic components traditionally used towards the use of soft flexible systems. Soft robotic systems can be both safer for humans to be close to due to their compliance [39] but they can also be a lower risk to the overall working environment since if there is a collision the robot should just deform around the object and thus not damage the structure. Soft robots have been used in the field for marine life sampling [40] and recent developments have allowed them to dive to the depths required for deep-sea foundation monitoring [41]. A comprehensive review of area of soft robotics for marine environments has been created by Aracri et al. [42].

RAS are certified as safe upon their purchase from a manufacturer. However, from this point onwards, there is no current method to verify that a robot is safe and certified as fully operational for deployment. A future enabler in the trustworthy deployment of RAS and AI includes the servitization of these assets. This is defined as the requirement to inspect a robotic platform to ensure that the platform is certified as operationally reliable, safe and has the ability to function fully. The service procedure should be set out by the manufacturer and regulated by a governing body. The service schedule recommends specific checks and replacement parts including actuators and sensors at certain intervals based on a reliability model of the component. As Cyber-Physical Systems (CPS) are deployed in more remote scenarios, for example, deployed further from the shoreline in the offshore sector, an increasing requirement is to ensure the
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reliability of these assets for Beyond Visual Line of Sight (BVLOS) operations. This includes the reliability of robotics which can utilize run-time reliability ontologies and infrastructure which employs effective asset management procedures.

For the use of any RAS assets an operator would typically begin to learn how to control a robot through a simulator and once experienced on that system they would be training in-situ on the robots themselves. Once given operational control the operator would normally view a control panel and a view from any onboard camera on a computer screen. This view can be limiting for the operator and as asset inspection and maintenance has progressed and bandwidth for robotic systems have increased the use of Virtual Reality (VR), Augmented Reality (AR) and mixed reality (MR) have also begun to be used. VR has seen an increasing use for robotic operational training [43, 44] while the use of AR and MR is increasing in usage when the robot is being controlled [45, 46].

It can be seen that even before the pandemic there was a shift to using sensorization, RAS, VR and AR, the restrictions placed upon workers for travel and office work has accelerated the uptake and investment in the trends which augment remote work. The next section explains the current asset management methodologies that are used in the energy industry and how they are developing to incorporate an increase in CPS.

3. Asset Management Methodologies

The energy industry requires a continuous year-round cycle of maintenance which requires the permanent presence of a Condition and Performance Monitoring (CPM) system [47]. The CPM systems are designed to maximize production uptime and asset availability. CPM systems react to the asset managers need to continuously demonstrate ‘fitness for service’ and improve the understanding of an assets condition. This supports the decision-making process for de-rating, process optimization and scheduling for remedial action and maintenance. There is also an objective of providing evidence-based knowledge to support the extension of components Remaining Useful Life (RUL) where this justification ties with brown fields.

Technological advancements have enabled oil and gas deployments to expand into deep and ultra-deep waters [48, 49] however, this presents challenges due to more hazardous weather conditions and increasing distance to the shoreline. It is therefore essential to improve an understanding of the numerous potential issues related with deployment and operation in unfamiliar environments and accept full answerability for the subsequent economic consequences. Subsea well system interventions and repairs become increasingly expensive due to longer delays because of availability and mobilization durations for the required intervention vessels. These costs increase alongside the distance from a fault to the shoreline.

Short- and long-term success and efficiency of the management of inspection, maintenance and repair activities directly affect Key Performance Indicators (KPI) including:

1. **Availability:** How many assets are ready for operation?
2. **Reliability:** Maintenance should be the first priority to ensure reliability. This has been considered a key objective in subsea operations conducted by the O&G sector.
3. **Life Cycle Costs:** Neglected maintenance results in more expensive remedial action as failing equipment needs to be replaced which reduces the life cycle
costs of the equipment and increases costs. Scheduled maintenance should instead be optimized where the cost requirements for the life cycle of the asset must be considered as the failures per equipment per time of operation.

4. **Safety:** Assets should have the capability to perform safely and must follow set safety standards. The safety parameters must be designed for all types of assets. A measurement should be created to measure the safety parameter per asset per maintenance level and repair. An asset is only available as fully operational if this measurement is 0%.

5. **Asset Management Satisfaction:** A direct impact on the asset manager satisfaction will be achieved from an effective maintenance which has been performed to high quality and will last a long duration. The asset manager is affected by the status monitoring and maintenance of the equipment.

One method that is being used to maximize the Remaining Useful Life (RUL) of assets and maintain peak system-level effectiveness, is that a myriad of industries have been transitioning from traditional reactive condition-based monitoring and maintenance systems to a predictive maintenance model. This transition is essential to gain a Return on Investment (ROI) and reach performance targets. To manage KPIs more effectively and provide support for asset managers with a systematic work process for successfully managing technical risk and uncertainties, this section presents a knowledge representation framework for end-to-end intelligent asset maintenance systems and processes. This work also presents the groundwork in developing a maintenance knowledge-based model describing the O&G environments and similar industrial scenarios.

### 3.1 Maintenance Processes in the Oil and Gas Industry

Complex industrial assets including floating production, storage, and offloading (FPSO) vessels, underwater wells and pipelines require maintenance which is often an intricate and critical task. Maintenance activities include techniques such as on-condition monitoring and predictive maintenance. Different types of maintenance outlining the flow of actions for each are displayed in Fig. 13.1 [50].

Standard maintenance is typically performed with respect to time. This usually relates to safety-critical items, including valves and Emergency Shut Down (ESD) systems. During this period, maintenance regimes and records for all assets must be kept and stored efficiently. This can be a time-consuming task unless a modern well system control and data gathering system is available and in place. There is also the problem that assets can deteriorate just as rapidly if they are being unused as compared to operational every day; the items which deteriorate will vary for each case. Condition monitoring is completed by examining the operation of the equipment and changing components or parts of the equipment shows signs of wear beyond preset limits. On-board monitoring usually does the inspection where the data is stored and then downloaded for the maintenance facility. Predictive maintenance systems are focused on the analysis of current equipment states with the objective to expose emerging problems which will prevent catastrophic failure via device maintenance. The aim of predictive maintenance is to detect smaller problems which require smaller remedial action rather than large failures. Predictive maintenance can allow for the modification of system parameters, replacement or tuning of components and drives down expenses for equipment upkeep as faults and failures increase the downtime of an asset and can damage devices severely.
Predictive maintenance regimes require access to the condition of assets to both look at data and the knowledge which can be obtained from the data. Reasoning algorithms within embedded decision-making agents can optimize the long-term management of heterogeneous assets and allow for a rapid response to events by autonomously coupling resource capabilities with alerts in real-time.

A challenge represented in CPM is that these applications are mono domain, targeting only systems (i.e. flowlines or control systems). Therefore, it often isolates the platforms and restricts the potential of multiple coordinated actions between adaptive collaborative systems.

In typical information flows, the main use of the data acquisition systems is to collect information from the sensor data. In order to embed tools which can support decision making and interoperability, it is required that these systems have the capability to deal with and understand the highly complex and dynamic environments they are installed in. Decision support tools are therefore constricted to the quality and scope of the information available.

Shared knowledge representation is therefore required to give them the required common situational awareness. Knowledge from two sources can provide this information: the domain knowledge retrieved by the expert and the inferred knowledge from the processed sensor data. For these two examples, it is essential for the data to be stored, accessed, and shared efficiently via deliberative agents in near to run time.

### 3.2 Data Flow in Maintenance Processes

Maintenance processes depend on comprehensive and timely delivery of information from embedded data gathering systems to the persons performing the required operations. This enables for the integration of maintenance related information from multiple sources into an automated maintenance system in order to give appropriate maintenance support. The variety of data contributes to the maintenance process and is represented in the data flow illustrated in Fig. 13.2 which represents the typical life cycle of maintenance activities [50].

![Figure 13.1: Types of maintenance and their succession of events [51].](image-url)
When observing the maintenance environment, knowledge is produced by interactions among systems, system observers, obstacles, engineering objects and instruments. Complex system interactions must be forwarded into infrastructural layers established on the knowledge of a system, which must be dedicated to human and data communications. For the environment which requires a large amount of problem solving, their collective vocabularies must be associated with the communication crossing the layers. The synthesis of this information would impact on the knowledge technologies employed for solving engineering problems encountered within the maintenance domain.

### 3.3 Knowledge-based System for Maintenance Domain

Maintenance, as with any other engineering process, is the human effort to alter or facilitate an environment to become more suitable or responsive to perceived human requirements. Many different physical outputs are created as a result; define, design, develop or maintain a system. A wide range of personnel are involved in engineering; engineers, managers and others who produce artefacts. The majority of knowledge about a system is created from a combination of human observations, designs and experiments as a result. This includes ensuring that a system and the relevant personnel, all know what they know and when they need to know it; resulting in mutualistic and commensalistic symbiosis. With a computing perspective, knowledge management must be implemented. This must encapsulate its meta-systems in whichever forms to show how knowledge is grounded from a level of engineering to the level of business organization that managed the engineering processes.

Logical extensions can be made to integrate information in knowledge-based systems. Therefore, the concept of knowledge is presented within this chapter with attention to each details as this is considered a driving element of intelligent maintenance systems. This commences with the basic definition of the knowledge-
based system where this task is abstract and extends to the maintenance domain for O&G. The knowledge-based system will be constructed with a number of different layers to represent different aspects of the systems as maintenance activities.

A key objective which is presented in this chapter is to establish a knowledge-based system for the maintenance domain with coherence of the interaction between infrastructure and data, objects, humans, systems, devices and communications to achieve or solve problems. This also includes software tools and all support systems including computers, web and data networks.

For a coherent infrastructure all the involved interactions, and some aspects and system concepts need to be considered before establishing the main requirements for the maintenance of a knowledge-based system.

- Models can be created in a wide range of domains—this includes a range of viable alternatives. The most effective solution almost always depends on the possible extensions and applications.
- The development of a knowledge-based system is an iterative process.
- Concepts in the system should be close to objects (physical or logical) and relationships in the domain of interest, e.g., asset maintenance domain. These are most likely to be nouns (objects) or verbs (relationships) in sentences that describe the domain.

Going into further detail, the implementation of a knowledge-based system and how detailed or general the system will be designed to be will guide many of the decisions for the model. Among a number of options, some aspects can be determined or designed to work more effectively for the projected task, be more intuitive, more extensible and with increased maintainability. Furthermore, the knowledge-based system facilitates a model of reality of the world where the concepts within the system must reflect this reality. Once the first version of the system is defined, it can then be evaluated and debugged by imposing it on an application or for problem solving methods or by discussion with experts in the field. This would then result in the initial model then being revised and improved where an iterative process of design continues throughout the entire lifecycle of a knowledge-based system.

### 3.4 Model for Predictive Maintenance

As discussed previously, predictive maintenance for assets in the O&G environment is a knowledge-intensive task which tends to be performed or supervised by human experts. The primary objective of the predictive maintenance processes is to improve equipment reliability by identifying problems before they cause failure and further damage which will render it as a catastrophic failure and increase the lifecycle costs of the asset. The secondary objective is to provide advanced warning of developing problems before the equipment fails catastrophically during operations in production. In order to avoid an unexpected breakdown of the system, its goal is to predict when and what maintenance actions are required. Figure 13.3 illustrates all the inputs and outputs which should be considered in the intelligent maintenance process of a system for the realization of predictive maintenance.

Embedded tools and annotated sensor data serves as an input for the prediction and diagnostic task to produce optimum fault detection. Diagnostic and prediction outputs serve as an input to the planning task involving sub-tasks such as fault recovery and on-line learning. For constructing a model, Fig. 13.3 describes the array of tasks...
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and their breakdown into subtasks which are required. If a list of input/output roles are in place to serve as knowledge roles is created where the most important elements can be created by different knowledge types. These knowledge types include domain, concepts, relations or rules and are described as follows:

- **Parameter**: A calculated or measured quantity whose value can detect abnormal behaviour.
- **Source**: An element that can be observed or detected.
- **Symptom**: A negative source.
- **Norm**: Expected values of a parameter for normal condition.
- **Discrepancy**: A quantified difference to the norm.
- **Fault**: Cause of symptom.
- **Location**: Where a symptom or fault is found.
- **Action**: An activity to eliminate a fault or to improve situation.

The knowledge roles could represent the meta-concepts in the knowledge-based system and could be expressed in the relational task-domain (fault detection – well system). This can be observed as in Fig.13.3 due to the several domain knowledge models (i.e. ontologies [52, 53]) which can be constructed for the scenario of maintenance in the O&G environment. The models could be created for the wells where domain models could encapsulate the maintenance activities, fault detection and diagnostics. These domain models represent the knowledge of the domain independently of their own use. However, the application of predictive maintenance as a knowledge-based system will employ existing domain models using relations and concepts from these models to optimize knowledge transfer.

The domain models are where the data is collected, distributed and measured. The reports are then circulated where groups can participate and communicate with each other. Data in a physics-based infrastructure cannot be explained merely as a consequence of a differing coherence of an assertion. They depend on where the sensors are situated, where the data is channelled, who makes the assertion, how the data is stored and filtered and what methods are used to understand and explain the observed phenomenon. Therefore, the knowledge-based system is systematically
constrained by the physics-based infrastructure. The prior knowledge for the model design must be closely inherent to understandings of the physical systems as well as practical experience of the systems. Therefore, the knowledge-based system is systematically constrained by the physics-based infrastructure. The priori knowledge for the model design must be closely inherent to the understanding of physical systems alongside the practical experience of the systems. A process which completes problem solving for a given application can be supported by ‘content’ from the prior system information. Another interactive layer is human-oriented.

For example, the maintenance of an engine, used to be a traditional event where an engineer would answer a repair-call with the parts and tools required to fix the issue. It now includes how to detect the first sign of a developing problem from the engine before it reaches a failure. Engineers can analyze the failure of equipment and utilize forecasting to assess the chance of failure of the same equipment failing in the same asset or other units, or proceed with data gathering, data clustering, testing, fault or defect diagnosis, planning spare parts, making recommendations, reporting major factors affecting a systems life, all in a technical and timely manner. All layers are meaningful and usable only when a system observer participates in a particular communication. Whether a maintenance engineer can exploit in an elliptical or anaphoric resolution is dependent on the role that the engineer has most recently played in the communication in the physics-based infrastructure.

The domain model is a description of the real-world things of interest and consists of a set of conceptual classes, their associations and attributes modelled with knowledge-based class descriptions. In the O&G example, the domain model consists of faults which can be described by a failure event. Furthermore, condition monitoring methodologies are employed to trigger predictive action when failure states are predicted. Predictive maintenance actions can be classified as a subclass of a proactive maintenance type similar to a scheduled maintenance action. The possibility of a fault can be reduced due to proactive maintenance. In case of a failure state, reactive maintenance action, or on-condition, restores the system state to normal. Reactive and proactive maintenance actions are subclasses of maintenance actions. All these concepts related to the asset maintenance domain are presented in Fig. 13, where it can represent the initial knowledge model to anchor the collaborative approach in the knowledge model design.

The Maintenance Type is the key concept of this model. A fault triggers the Maintenance Type depending on the nature of the problem (Existing Fault or Incipient Fault) the maintenance type is classified into two different and disjoint Corrective Maintenance or Predictive Maintenance. Associated to each Maintenance Type individual, there is a Work Order, which lists the variety of Maintenance Activity that are necessary to recover or repair the fault. In other words, the model deals with both the forecastable faults and some faults which are unknown or exceptional in their evolution. This trigger different classifications of responses. The main relationships associating these concepts are:

- Fault Requires Maintenance Type
- Maintenance Type has Work Order
- Work Order has First Maintenance Activity
- Maintenance Activity has Next Maintenance Activity
Feedback can be taken from several participants in the collaborative design process of the knowledge-based model. The sub-classification of the maintenance actions to proactive and on-condition is unnecessary. These options can be represented as instances of the maintenance action class. Furthermore, the maintenance schedule could be linked to the respective maintenance actions.

The primary aim of condition monitoring techniques is to predict the failure state, but the method could not trigger any maintenance action. Failures can be prevented by the maintenance action where the condition monitoring is associated with a number of limited failures. Also, each failure state could not be associated with a condition monitoring method.

In viewing Fig. 13.4, doubts could be made about the differences between the failure state and failure event. A fault is a possibility for or an existence of a failure event or state. However, an event is a state change of a system. This enables an event to be described with the resulting state or a state with the causing event. Events of interest that affect assets in the O&G domain in the shape of a Failure Mode and Effective Analysis (FMEA) can be seen in Table 13.1.

### 3.5 System Architecture

A number of different layers should be included in the construction of the knowledge-based system. The layers are used to represent different aspects of the system, for information integrating for intelligent monitoring, which is established on a multi-tier architecture and a common terminology. A view of the architecture for information integration is displayed in Fig.13.5. From the ground up, there is an abstraction and aggregation process in place, which abstracts from the low-level, proprietary information to higher-level information. This is enhanced by the semantics which are embedded in the knowledge-based model.
Table 13.1: Characteristics of events and effects considered in the knowledge-based model [51]

<table>
<thead>
<tr>
<th>Event</th>
<th>Effect duration</th>
<th>Event duration</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatigue</td>
<td>Dynamic, Vibration</td>
<td>Continuous</td>
<td>Continuous</td>
</tr>
<tr>
<td>Excessive loading</td>
<td>Static, Quasi-static,</td>
<td>Short or</td>
<td>Sudden</td>
</tr>
<tr>
<td></td>
<td>Dynamic</td>
<td>continuous</td>
<td></td>
</tr>
<tr>
<td>Shock loading</td>
<td>Vibration</td>
<td>Quick</td>
<td>Sudden</td>
</tr>
<tr>
<td>Force monitoring</td>
<td>Static, Quasi-static,</td>
<td>Change, Drift</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td>Dynamic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shape monitoring</td>
<td>Static</td>
<td>Long</td>
<td>Regular</td>
</tr>
<tr>
<td>Third party</td>
<td>Dynamic, Vibration</td>
<td>Quick, Change</td>
<td>Sudden</td>
</tr>
<tr>
<td>interference</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluid properties</td>
<td>Static, Quasi-static,</td>
<td>Change</td>
<td>Sudden</td>
</tr>
<tr>
<td></td>
<td>Dynamic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leak</td>
<td>Dynamic, Vibration</td>
<td>Change</td>
<td>Sudden</td>
</tr>
</tbody>
</table>

Figure 13.5: Layered architecture for integrating distributed monitoring data [51].
• **Real-World Information:** Real-world data is accessible via the lower level. This is gathered from sensors or the digital version which is stored in databases (for example in some databases of the stakeholder, in geo information systems, or on the internet). The predominant challenge for data acquisition and later integration on this layer is heterogeneity.

• **Semantic Transformation:** The second layer is where the software parsers and adapters are situated. These transform real-world data into a common language. The output of the different software parsers and adapters are kept in distributed repositories. Consistent descriptions between the predictive maintenance domain model and the semantics of the generated data (relations and properties of referenced objects) are important.

• **Aggregation and Persistence:** Repositories, databases and distributed information are integrated within this layer.

• **Predictive Maintenance Domain Model:** This layer represents an XML-based data model which uses description logics for stipulating the terminology of the predictive maintenance domain as well as the O&G domain.

• **Distributed Reasoning** [54]: This layer comprises of reasoners. This can be described as a software-based inference engine which interprets and analyses information by deriving additional data by employing descriptive logic.

• **Intelligent Services:** The top layer consists of services and maintenance agents (software agents) which can collaborate autonomously with each other to analyse certain fault scenarios. This supports corresponding decision-making tasks (for example predictive maintenance: a maintenance working order for an asset-based on symptom analysis).

4. **Offshore Energy Case Study**

One of the largest EPSRC funded UK based academic and industry collaboration for robotics in extreme environments is the UK Robotics and Artificial Intelligence Hub for Offshore Robotics for Certification of Assets (ORCA Hub). The ORCA Hub is a four year, multi-organization project with the primary goal to use teams of robots and Autonomous Intelligent Systems (AIS) on remote energy platforms to facilitate cost-effective, secure and enhanced efficient operational practices [46]. The ORCA Hub is a collaboration between leading industrial companies with academic institutions. The creation of a fully autonomous offshore platform, being governed and inspected from the mainland is the ultimate goal of the ORCA Hub, as it would allow for a reduction in the number of workers in hazardous environments. The idealized system created in the ORCA Hub is comprised of the remote energy platform, related assets, monitoring systems, and the heterogeneous robotic systems (aerial, surface, and marine robots) required to ensure the platforms continuous autonomous functionality.

To achieve the ORCA Hub’s goal of autonomous offshore infrastructure a host of different robotic and sensors systems are required to be able to operate independently and in conjunction with each other and humans. There are multiple different areas that are required to be sensorized for accurate monitoring on an offshore energy platform. For example, on a wind turbine the blades require inspection for corrosion, water ingress and internal damage, the internal monopile, housing and nacelle require an array of sensors monitoring for different environmental measurands such as structural vibration, machine vibration, weld strain, humidity, pressure and temperature, the
underwater foundation of the turbine requires inspection for scour, corrosion in the foundation and damage to the outlet pipes.

To monitor the different areas of an offshore platform there needs to be a combination of permanently deployed sensors and other inspection methods that can be used periodically and when required. The Limpet sensor [55, 56] is a multi-sensor platform created to be deployed by humans or robots wherever it is required. Each Limpet contains a temperature, vibration, strain, humidity, pressure, and light sensor as well as the ability to have custom sensors plugged into it. They offer multiple communication modalities such as infrared, Lo-Ra, Wi-Fi and acoustic. Robot Operating System (ROS) is integrated into each Limpet allowing for data transfer between the robots used in the ORCA Hub. For inspection of wind turbine blades and insulated areas a Frequency-Modulated Continuous-Wave (FMCW) has been developed [57]. To inspect metallic sections an Electromagnetic-acoustic transducers (EMAT) sensor has been developed and deployed [58].

How to deploy and these sensors in extreme environments is a key part of ORCA Hub mission and there are multiple robots being used. For terrestrial requirements, the Husky a wheeled robot developed by Clearpath Robotics [59] and the ANYmalC a quadruped robot developed by ANYbotics [60] have been used. Quadruped robots can be used to overcome obstacles that regular tracked or wheeled robots cannot achieve such as stairs or uneven terrain [61]. Aerial inspections are conducted via drones [62]. To conduct aerial operations different anchoring and perching methods [63], mobile polymer repair systems [64] as well as multiple flying morphologies [65] that could allow a drone to also perform an underwater inspection [66] were developed. Underwater inspection comes from a range of different AUV’s such as the Falcon [67] and BlueROV2 [68].

To both accurately show where all the sensors and robots are located in an industrial site a DT [69] can be implemented. A DT will show a digital replica of the industrial site and can be both used for accurate simulation before robots are deployed and as real-time displays of the data being gathered by the different systems functioning at that point.

Another key and often overlooked element of implementing robotic systems into remote areas is how they will interact with the humans operating them both remotely and potentially in the field, this area is known as Human-Robot Interaction (HRI). Within the ORCA Hub the MIRIAM (Multimodal Intelligent inteRactIon for Autonomous systeMs) [70] system was created as a way for operators to query their robotics in real-time and using natural language. Work was required on how natural language could be used to command robots and to understand the information they are feeding back to the operators. Trust between human and robots is essential when it comes to performing complex and dangerous tasks [71, 72]. The primary method is through the use of natural language interactions to allow for the robot’s decisions to be made in a transparent and understandable manner.

While the operation of a robot remote should not demand a large degree of physical exertion there can be a greater mental strain placed on the operator. With this strain in mind researchers have also developed ways of eye-tracking [73] and cognitive load [74, 75] that can be combined with the remote operating system to create a safer working environment.

With such a broad range of robotic and sensors systems being developed to be deployed together and to function for long periods of time with minimal to no human
interaction the entire robotic ecology/system needs to be carefully designed and managed. The method proposed to efficiently and effectively do this is through the creation of a Symbiotic System of Systems Approach (SSOSA).

4.1 Design of the Symbiotic System of Systems

An assessment of the top-down challenges of Robotics and AI (RAI) and Operations and Maintenance (O&M) allows for a digital architecture which enhances the symbiosis to be created, which includes planning, functional, safety and operational necessities to ensure foresight and resilient autonomous missions. The inclusion of a SSOSA results in the creation of a symbiotic ecosystem across people, robotic platforms, infrastructure, environment, and systems.

Smart environments, CPS, robotic platforms and humans are all elements included within Symbiotic RAI relationships and are able to cooperate when performing tasks [76]. Mutualism, commensalism and parasitism are the three most fundamental forms of symbiosis. Parasitism is defined as a relationship where only the parasitic component benefits, while the host component is harmed. Interactions between one element, resulting in one being unaffected while the other benefits, is defined as commensalism. Mutualism defines a relationship where both elements benefit [77, 78].

Key barriers inhibiting the commercialization of autonomous systems include operational resilience and safety compliance in BVLOS robotics, where impediments in the development and deployment of state-of-the-art RAS were identified due to the limitations in interaction between Cooperation, Collaboration and Corroboration (C³). This includes the interaction with human, environment, infrastructure and autonomous systems. These three interactions are based on inter-intra (internal and external) goals and laws, for instance the envelope of a mission which has been predefined. In the design of a SSOSA, C³ results in collaborative governance to ensure the resilience of an autonomous mission, increases safety and creates a hyper enabled overview for the human operator. This accelerates the future ability to methodically characterize trusted relationships, especially as robots become resident systems and humans operate remotely.

As inspired by nature, data (information) interactions and awareness of the system are regulated by guidelines to ensure reliable communications. The SSOSA and the created Symbiotic Digital Architecture (SDA) generates an upgraded environment and model for hyper-enabled safety and operational requirements alongside knowledge distribution/sharing in autonomously operated functions and isolated robotic operators. Collaborative governance can be reached via the implementation of an ontology which is driven by AI on a RAS to monitor the resilience of the vehicle in real-time, in conjunction with edge analytics for an improvement in holistic transparency/visibility for a system. This offers a continued tactical viewpoint of a remote resource, ensuring safety governance is always at the front and centre of a mission.

In our roadmap, we define two steps in the advancement towards trusted autonomy, self-certification, and symbiosis across robotic, infrastructure and environmental systems. These paradigms signify increasing tiers of mission resilience and safety, allowing for an acceleration in effective servitization to ensure alignment of the conditions required for a progressively automated seaward ecosystem. This chapter focuses on the first tier — “Adapt and Survive” with our next objective our roadmap aimed at the second tier – “Adapt and Thrive”.
1st Tier – Adapt and Survive: An autonomous mission or operation with a mission envelope that is predefined. The architecture of the system can assess: any effects of the variables within a situation from the infrastructure, robot reliability, environment and operator interactions; collaborating and distributing data and information with a remote operator; negating unknown and known risks to the safety and reliability of the CPS and its mission. Commensalism and mutualism are achieved to ensure survivability of a CPS and the completion of the objectives of a mission without violating safety governance [79].

2nd Tier – Adapt and Thrive: An enhancement of the standards outlined in the first tier with the addition of utilizing a distribution map of knowledge which has the ability to recommend options for an observer on updated priorities of the multi-objective mission. This incorporates the RAS evaluating unanticipated variables, their outcomes and creating solutions for optimization of a mission. This develops the symbiotic relationship further where CPS are at the forefront. Resource sharing via a DT which has minimal elements of parasitic capabilities can make sure a CPS thrives however, in no way to the detriment of another RAS [79].

The SDA and SSOSA have been initially developed for the needs of the offshore renewable energy sector however, the intent is for a broader facilitation for resident and BVLOS RAS via shared operational and resilience requirements. Innovative information flows between crucial front-end systems and decision assistance across robot, isolated/remote operator and infrastructure created via a digital synthetic environment with bidirectional interaction (C³).

4.2 Symbiotic Interactions and C³ Governance

Symbiotic relationships and interactions include formal and informal interactions that operate alongside collaborative governance. Augmented learning processes, trusted autonomy, decision-making, and problem-solving are critical in the integration of RAS/I and human interaction that results in human-robot systems. Multiple types of technologies enable symbiosis between a human and robot depending on the conditions of the function. Natural language, mouse-based or gesture interaction for MR is included within these elements of symbiotic interaction [80]. Typically, only a single element of symbiosis is captured by these technologies as illustrated within Fig. 13.6 (Previous Autonomous Systems); cooperation, collaboration, or corroboration. The SSOSA further develops the symbiotic interactions across systems to achieve collaborative governance.

![Diagram highlighting the barriers in the current state-of-the-art and the route to collaborative governance via a SSOSA.](image-url)
The interrelationships between the host and symbiont represents the symbiotic interactions. We define a symbiont as a system that requires an interaction between another system’s elements. The symbiont tends to depend on the host resources for it to operate effectively [81]. Rudimental symbiotic interactions are represented in Table 13.2. When a positive outcome is reached by both symbiont and host, mutualism exists in the relationship. The interaction between a robot and human can be included under this definition as the human benefits from the RAS completing objectives and the host benefits as the operator has the interaction capability to advise on the CPS operations. A commensalistic relationship is achieved when the host is unaffected and symbiont obtains a positive result. An example includes improving human efficiency via an AI bot, yet receiving no benefits in return. When the symbiont benefits at the expense of the host, the symbiont is classed as a parasite. When there is a mix of new and legacy systems the interactions between technologies could be observed as parasitic due to resource competition with the host, e.g., power drain. An example of this includes if a robotic platform (symbiont) had the capability to connect and steal charge from another robotic platform (host) for the symbiont power supply to accomplish its mission. This could detriment the mission envelope of the host as it would have a reduced battery for the completion of task. Intra-inter processes and collaborations will always generate symbiotic competition for resources. The problem we propose includes: to what degree do the decisions made become detrimental to an objective or mission? For example, a human operator may have time limitations on the completion of a project which uses a RAS. If the RAS acquires a fault, depending on the system, the human operator could override the ontology to continue the mission at the detriment of the robotic platform. Therefore, the human becomes a parasite to the system. However, automation via the development of ontologies can reduce this effect to ensure beneficial symbiotic relationships and ensure predetermined rules and regulations are followed.

<table>
<thead>
<tr>
<th>Type of interaction</th>
<th>Symbiont</th>
<th>Host</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mutualism</td>
<td>Positive</td>
<td>Positive</td>
</tr>
<tr>
<td>Commensalism</td>
<td>Positive</td>
<td>Neutral</td>
</tr>
<tr>
<td>Parasitic</td>
<td>Positive</td>
<td>Negative</td>
</tr>
</tbody>
</table>

The ability to control a system remotely is defined as teleoperation. This enables a human to collaborate with a robot and can be achieved via line of sight or remotely via real-time information on a computer display. The mutualistic relationship via these types of technologies, where visualization supports the observer to improve the functionality of the robot, benefits both aspects of the paired connection. Increased levels of autonomy enable RAS to produce run-time maps of the operational environment from LiDAR sensors for path planning, where MR devices can be implemented to provide novel methods to visualize RAS and CPS [83–85].

Cooperation is often achieved via speech recognition technology which allows human operators to interact with CPS, often employed by sectors, which deal with increasingly large volumes of data [86, 87]. An information transaction hub of data can be created by the employing a DT which can virtualize and control assets for
remote monitoring, interaction, and navigation. This is a form of commensalism due to the human benefitting from the relationship across the systems. The cloud computing infrastructure handles the computational burden from speech processing, leading to no effect on the performance of the robot or autonomous system, whilst augmenting the ability of the operator. Devices can be controlled with no physical inputs via the implementation of ‘call out’ instructions. To ensure seamless integration of ‘call out’ instructions, it is paramount that they are designed to be intuitive to the operation and operator, however, it is difficult for all commands to be voice-based [88].

Continuous missions typically use input systems such as standard controllers due to the operations and motions to new locations, which are not determined in the mission plan, this is the reason why voice commands are less prominent. However, voice commands which allow the robotic system to autonomously move to a directory of predetermined locations (e.g. “home” or “generator”) are effective solutions [89]. Software accessibility is improved via Speech recognition, a control method only surpassed only by touch-based interactions for speed of operation for senior users [89]. Allowing for a twin to be accessible on more devices (other than a standard desktop) such as virtual reality headsets which have zero physical inputs, allowing for on-site operations to be performed.

MR devices, including the Microsoft HoloLens, operate as a cooperative technology using gesticulation via a user interface. Design standards are yet to be fully created for this technology, however, the HoloLens offers pre-created gestures within its functionality. Gestures including an ‘air tap’ and ‘dragging’ allows for interaction via sliders and option controls within in the 3D environment, in addition to the capability to reposition on-screen elements. A distinctive feature these devices offer is the capacity to visualize the environment with the virtual robot positioned within, evaluating the space for safe robot operation. The processing load is on the HoloLens, which has a devoted processor and is represented as commensalistic collaboration. The gestures create benefit to the ability of the operator to interact, whilst not being negative to the functionality of the RAS. The operation of the HoloLens is displayed in Fig. 13.7, demonstrating interaction with a model by accessing the outcomes from the DT of an offshore asset without having an influence on the functionality of the wind farm array [90].

Undesirable and unforeseen events are minimized by ensuring operators have the ability to interact with a DT simulation [91]. The comparison and accuracy of outcomes in the digital environment compared to the deployed asset establishes corroboration. Integrating this methodology with resilient and different modes from input systems protects and maintains trust in the application. The combination of collaboration and corroboration is accomplished in the DT as the remote operator may terminate the operation of a CPS when completing any objectives during a mission in run-time. Actionable information ensures that an operational overview is always available via the DT. Mutualistic and commensalistic relationships are achieved between the symbiont (operator) and host (robotic platform) to ensure there is resilience to the mission envelope and performance of the CPS. Twins date back to the 1960s in the simulations of the National Aeronautics and Space Administration (NASA) Apollo 13 mission. A physical analogue of the command module was designed to steer the malfunctioning mission on its return to earth following a crucial system failure on the vessel [92]. Recently, improvements in newly available and easy access to hardware have facilitated extensive use of DTs to observe and run simulations to attain outcomes, possibilities and incorporate training sector-wide [93–97].
We discover a bottleneck in the current trajectory of robotic integration of systems defined under symbiotic envelopes. Present systems, as discussed previously in this section, are restricted to reaching a single aspect of either collaboration, corroboration or cooperation. To further advance symbiotic relations, it is vital that the combination and communication between $C^3$ is achieved in collaborative governance between infrastructure, people, autonomous systems and environment.

Additional instances of symbiotic interactions are clustered into the following groups and presented in Table 13.3. A human collaborator can be considered as a symbiotic relationship and comprises of a relationship between a person and RAS. This adds additional safety characteristics for a robot to maintain distance from humans or to allow robots to work in a shared workspace. Another partnership achieved includes multi-platform, which can include the symbiosis between the coordination of robots or robotic swarms during a mission. The Internet of Things (IoT) allows infrastructural sensors to be paired alongside DTs of buildings and includes overview and control of climates, access areas and associated autonomous systems. Asset integrity is an active area of development for use alongside DTs and enables fault detection via structural health monitoring sensors to be displayed in the synthetic environment and may also provide systems diagnoses to an operator. The application of a SSOSA gives the opportunity to define and include multifaceted architectures and processes within the systems engineering society.

<table>
<thead>
<tr>
<th>Symbiotic relationship</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human Collaborator</td>
<td>[98–102]</td>
</tr>
<tr>
<td>Multi-Platform</td>
<td>[101, 103–105]</td>
</tr>
<tr>
<td>Infrastructural Sensors</td>
<td>[106–108]</td>
</tr>
<tr>
<td>Asset Integrity Inspection</td>
<td>[109–111]</td>
</tr>
<tr>
<td>System of Systems</td>
<td>[112–114]</td>
</tr>
</tbody>
</table>
4.3 Symbiotic Digital Architecture to Enhance Resilience and Safety Compliance

Ensuring the safety of any RAS represents a specific challenge faced by human operators. Although many standards are considered as safe by legislators for robotic systems; safety criteria, including ISO 61508 and domain-specific standards including ISO 15066 (collaborative robots), ISO 10218 (industrial robots), or RTCA DO-178B/C (aerospace), and even ethical aspects (BS8611), none of which consider fully autonomous systems capable of handling important decisions which are critical to safety.

Within this subsection, the limits of the present system of system approaches and symbiotic systems are highlighted. A SSOSA consists of a variety of widely recognized symbiotic interactions, with the inclusion of the author’s specific innovative relationships, which further develop the state-of-the-art symbiosis and are presented within the sliced portions shown in Fig. 13.2. The advancement of DTs has fuelled the advancement of different symbiotic relationships. A DT allows a human operator to interactively with the synthetic environment and real-world platform as represented in Slice A. Majority of symbiotic system methods are widely recognized as multi-platform; symbiotic methods is accomplished via the cooperation or collaboration of several robots (Slice B). Infrastructural sensors provide an opportunity for corroboration as in Slice C. The devices are often used for localization to validate (corroborate) the position of a robot relative to its environment. Asset integrity inspection is represented by slice D and represents a symbiotic relationship under rapid developed and is discussed within this chapter. Cooperation with a DT ensures that asset integrity data is shared for an accurate representation of faults to the, often remote, end-user. Lastly, we create a novel symbiotic relationship represented in System of Systems (Slice E), where symbiosis is achieved between systems onboard an RAS. The approach uses bidirectional communications for assessment of mission updates/status and certification of a RASs own systems via a run-time reliability ontology. With this perspective, present “Symbiotic systems” can be described as symbiotic partnerships between a pair of sub-elements, for example, a DT and sub-element as in portions A-C. These usually also simply feature a single element of corroboration, cooperation or collaboration. This enables the designed SSOSA to represent all symbiotic partnerships to achieve C3 governance, as displayed by the hatched area in Fig. 13.8, with connections to a single, shared DT acting as the SSOSA boundary. Bidirectional means of communication between each symbiotic relation to the symbiotic ecosystem controlled via the DT ensures full symbiotic digitalization is achieved. A SSOSA is transferrable to ensure the integration of a range of RAS and infrastructural devices and sensors under the same framework. This work, and the relevant case study conducted by the ORCA Hub, has allowed Mitchell et al. [79] to construct the theory around the hypothesis and to show whether safety and trust is to be created via self-certification to work in an autonomous mission evaluation.

This section presents a SSOSA to ensure resilient autonomy as defined in Fig. 13.9. Symbiosis is achieved across systems within a RAS and via a DT utilizing bidirectional communications for run-time data interaction and representation. A symbiotic system is defined as the co-evolution and lifecycle learning with shared knowledge for mutualistic gain. We also describe a set of systems or system aspects which work together to provide a unique capability that none of the fundamental systems can achieve on its own as a system of systems approach [79]. This
Figure 13.8: Symbiotic digitalised ecosystem highlighting the implementation of symbiotic interactions within the SSOSA.

Figure 13.9: SSOSA definitions highlighting the challenges, solution, benefits and mission evaluation variables.
methodology is motivated with the perspective that an improvement in operating awareness can be accomplished via bidirectional exchange of knowledge from a DT, to enhance execution and promote life cycle advancement. The aggregation of data from across the RAS, environment, infrastructure and human operator will ensure this is completed.

The barriers which symbiotic systems will encounter include the creation of collaborative governance via a DT interface which creates confidence and trust for the human operators and the provision of an improved DT to classify system certification, operations report and shared data across systems without inducing information overload for the operator. Within the SSOSA, the DT elements are created to perform as the base of command-and-control for a mission which creates functionality, increases autonomy, enhances human trust, resilience during operations and compliance certification. A SSOSA secures several advantages due to the platform agnosticism within the SDA which is adaptable and scalable, featuring the bidirectional network for enhanced visibility or data-driven solutions during autonomy. This enables the architecture to be utilized to any commercial off-the-shelf robotic platforms, such as SPOT from Boston Dynamics. The SDA and system implementation process is modified appropriately depending on the sensors and actuators specific to the robotic platform.

Mutualism and commensalism is captured under the first tier, ‘Adapt and Survive’, of the SSOSA as defined at the start of the previous section. The utilization of a real-time ontology for reliability allows the symbiotic architecture created to assess the effects of a situation from variables across environment, infrastructure, RAS reliability and interaction for a remote operator. The incorporation of shared data from numerous deployed devices allows for data collected to be routed to the DT to allow collaboration and an overview for a remote human-in-the-loop. This allows for mitigation of unknown and known hazards and threats to the resilience and safety of the autonomous mission. A mission can be evaluated due to the closing of goals within the mission envelope whilst confirming safety compliance of the RAS under a survivability viewpoint.

In the future development of our SSOSA, we include a roadmap to tier 2, ‘Adapt and Thrive’, where a number of RAS employ a map of distributed knowledge to create recommendations for the human-in-the-loop on new mission priorities which have multi-objectives. This newly created information can be shared for many CPS autonomously and seamlessly integrated for mutualistic, commensalistic or parasitic advantage, however, by no means at the detriment of another CPS mission envelope. An example of this parasitic gain could include the data sharing of battery state of charge, where a RAS (symbiont) could deprive a host robotic platform of battery charge, but where the symbiont leaves enough charge for the host to still complete its planned mission objectives. We include the definition of a ‘Thriving’ SSOSA in our future objectives, where a robotic platform can overcome unforeseen events, necessitating autonomous departure from the mission objective, yet still achieving an optimized mission profile. The system can autonomously suggest solutions to threats to ensure mission permanence and continuity.

The creation of a run-time reliability ontology via edge analytics improves the visibility to present and imminent signs of failure. The quick evolution of different types of failure requires different revival strategies and should be designed into a reliability ontology. In the design of our ontology, this includes a recovery element
that instructs the RAS to proceed to an accessible and safe area in the event of a warning fault or future failure. This can become important as discussed in “Confined Environments” implementation, where humans may not be able to access a zone to recover a robot. Therefore, if a robot can make itself safe in a designated recovery zone, this may be a more effective option when compared to a robot stranded in an area inaccessible to humans.

Mutualism is achieved for safety compliance as the human and robot may communicate and interact via bidirectional communication systems. This is accomplished via human access to the DT for the assessment of mission status, whilst the RAS simultaneously prompts the human operator with fault diagnoses in real-time. The operator can terminate the mission at any point however, the reliability ontology gives the robotic platform the capability to make autonomous decisions to ensure a successful and safe mission envelope.

To verify the successful implementation of a SSOSA, demonstration variables must be fully considered and are listed under functional, operational, safety and planning of Fig. 13.9. A successful testing of our SSOSA within a confined space autonomous inspection evaluation is shown in the pilot studies section. Functional variables include ensuring run time data collection and bidirectional communications for a completely synchronized system architecture, precisely matching the representation within the DT. Operational variables are addressed via the system self-certification, which increase the autonomy and resilience onboard a robotic platform. Safety is a key variable in our SSOSA due to the requirement to support localization of humans, route planning and execution in opaque/challenging environments and operational verification reporting. Lastly, the design of a plan ensures that the reliability ontology is accurate to the deployed CPS. The ontology represents the decision-making hierarchy for the CPS and for reporting the status of a mission to the DT.

Our SSOSA incorporates a system integration process which is displayed within Fig. 13.10. The illustration presents the aspects of the sub-elements of the system and focuses on the symbiosis and resilience across the layers due to the C³ of data. The colour coding included in the figure is also utilized in Fig. 13.11 and Fig. 13.17 and provides a common differentiator between the different elements of the symbiotic architecture and robotic platform. The links between all subsystems are displayed within each layer and represent the addressed mission variables. The human interaction layer represents the human operator with the capabilities to interact with the mission via the DT. The DT user interface comprises of the functions for the operator to increase their operational overview of the deployed CPS. The data gathered from the FMCW radar is fed to the DT. The sensor represents a non-destructive asset integrity inspection payload employed on the robotic platform and can be used for surface and subsurface evaluation of materials. The Planning Domain Definition Language (PDDL) is the decision-making layer of the ontology and is connected to the software packages onboard the RAS. The Simultaneous Location and Mapping (SLAM) stack, ontology and motion planning are linked with the decision making as identified in the system integration process. Diagnostics from the actuators and internal sensors onboard the RAS and is processed by the ontology where the data collected from the cameras and LiDAR sensors is fed to the SLAM stack. The mobile base and manipulators receive the commands calculated from the motion planning element. The system integration process improves the resilience of each element, as each when functioning independently would have been unable to determine the required
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**Figure 13.10**: System integration process for the RAS utilized in the autonomous mission envelope.

**Figure 13.11**: SDA representing sub-elements from RAS to the remote human operator via bidirectional knowledge exchange.

answer. Therefore, with an applied SSOSA, mutualism via knowledge sharing and C3 is achieved across all systems.

With a focus on addressing the top-down requirements, alongside ground-up capability challenges, a SSOSA supports reliability in autonomous missions. To ensure actionable and time-critical information, the top-down requirements are mapped onto an architecture for reliable and trustworthy systems through the SDA (Fig. 13.11), which captures planning, safety compliance, operational and functional requirements of the SSOSA. The SDA also enables resilient intra symbiosis (within the robotic platform) and inter symbiosis (across robotic platforms and other systems). This includes the systems engineering with the incorporation of up to 1000 different sensors and architectures to be included under the same architecture.

The SDA is initiated by the user via the human-in-the-loop symbol. This permits the user to utilize the synthetic environment provided by the DT to gain actionable information from the resident CPS via the Graphical User Interface (GUI),
demonstrating bidirectionality. The DT has been designed to ensure knowledge can be obtained from MR devices, producing improved operational reporting, also available via a standard laptop. The asset data and all the information are presented within the digital environment of the real-world asset. Logical colour coding enables information such as components which present defects, to be displayed easily and identified by the human operator quickly.

The ghosting function is a meta-function of the DT and reduces the associated risks with any robotic arm operations by increasing safety. A visualization of the arms is accessible via the interface, where the arm trajectories can be simulated in the synthetic environment prior to operational deployment. This builds confidence across the SDA, as the human operator may identify any risks within the simulation via the visualization of the manipulation task prior to executing the planned path to the real-world robot. This leads to increased assurance for effective operation.

We include a novel radar sensing payload on-board the robotic platform which is included in our SDA. The FMCW radar sensor features the ability to distinguish humans through barriers which include walls and doors, thereby expanding the operational awareness of a robotic platform. The payload also provides support in opaque environments or when poor visibility impedes localization and where collision avoidance sensors become less capable. The sensor can also be utilized for asset integrity inspection, specifically when the sensor is used for the analysis of air to material interface, in addition to internal properties. This has been applied to integrity inspection of wind turbine blades, detection of corrosion precursors (with or without insulation) and inspection of metals within low dielectric civil infrastructures [57, 111].

The run-time reliability ontology block within the SDA supports adaptive mission planning which enables robustness, diagnosis, decision making, and prognosis. For a human observer who is remote to the field, this is useful as an improved understanding of the remaining useful life and state of health of important subsystems is provided, both at the mission planning stage and during run-time. To ensure effective operation of the ontology, front-end data and edge analytics is fed into rear-end functions via the DT. Bidirectional communications, supports connectivity and awareness via these data streams. The data collected from actuating systems and associated sensors are converted into actionable data when passed through the ontology to be presented to the human-in-the-loop. Actionable information includes recommended remedial action for the human operator to solve the problem. This could include stopping the mission or replacing components upon failure.

A diagnosis automaton within the AI-driven ontology is constructed for each critical element in the robotic platform including motor, battery, wheel, motor driver, integrated devices or single component. This includes components which are sensed or non-sensed. Distinct states can be designed for each segment of a system as displayed in Equations 1-4. C³ governance is outlined via the full adherence of the robot to the rules set in the ontology which minimize risk [41].

\[
\text{States} = \text{sensed, possible, normal} \quad (1)
\]
\[
\text{Sensed states} = \text{low current, high temperature, ...} \quad (2)
\]
\[
\text{Possible states} = \text{broken, aging, degrading, abnormal behaviour, ...} \quad (3)
\]
\[
\text{Normal states} = \text{on, off, ready, working, ...} \quad (4)
\]
Event transitions are scenarios or events which change the state of a component or system. These include temporal, internal, external or spatial events (each with differing degrees of probability). These transition events are:

\[
\text{Events} = \{\text{internal, time-driven, space-driven, external}\} \quad (5)
\]

Hierarchical relationships are utilized to convey the reliability ontology models, which include: ‘is-linked-to’ and ‘is-type-of’ or ‘is-connected-to’ relationship. For example, ‘x is-connected-to y’ [115].

Binary relationship = \{causality, implication, prevention, hierarchical, composition, aggregation, optional\} \quad (6)

The defining logic within the ontological binary interrelationship enables the \( C^3 \) across all sub-elements and systems under the SSOSA. Zaki et al. express a detailed formalism in [115].

Three types of binary relationships are linked to display the level of confidence in the relationship. These are: ‘causality’, ‘implication’ and ‘prevention’ [115]. E.g. ‘x must-cause y’, ‘x might-cause y’. Modalities combined with those relations include the following verbs:

- could (less possible)
- might/may (possibly)
- should (very likely)
- would (really likely)
- must (absolutely certain)

Each segment attains its own distinct properties, each having an influence on the inter- intrarelations within the system, such as: ‘reusability’, ‘dependency’, ‘availability’ and ‘validity’. E.g. x (is) reusable, x (is) stand-alone, x (is) available and x (is) valid [115].

A summary of these steps include:

A. Creation of an automaton for diagnosis, as built for each key segment of the CPS.
B. A description of the transitional connection across the states.
C. A description of the binary relationships across the states in differing elements.
D. Creation of the hierarchical model of the specified CPS.
E. Creation of a standard model of elements of the CPS.

5. Pilot Studies

The following section covers examples of cyber-physical implementation applicable to the energy sector. The pilot studies are confined environments, an onshore wind turbine test dock and nuclear storage tank decommissioning. These pilots showcase the SSOSA, and its components depicted in Fig. 13.17.

5.1 Confined Environments

Confined space environments present significant challenges to personnel and robotic maintenance regimes. A confined space typically has restricted access, leading to increased safety concerns; potential noxious fumes, reduced oxygen levels or risk of fires and more. Vigilance is paramount for both personnel and deployed autonomous systems [116, 117].
The piloting of the SDA to enhance safety compliance and resilience a physical onshore training facility was arranged to present similar challenges as an offshore substation platform. The environment included complex arrays of cabling and piping which included large elements of infrastructure such as a high-capacity transformer or offshore generator as in Fig. 13.12 seen here with a robotic platform deployed in a BVLOS confined space inspection mission. To ensure reliable communications a wireless base station was combined alongside a pair of wireless transceivers integrated with the robotic platform to mitigate wireless communication challenges.

The transit area includes a narrow corridor with a small amount of clearance on each side for the RAS, which resulted in an area of increased risk of collision. The confined space operational area consisted of a minimal area for manoeuvrability for the robotic platform. Path parameters were modified to enable for increased functionality during the navigation through the confined space whilst preserving safety via the avoidance of collisions. The case study discussed utilized an environment to replicate the highly challenging environment for sensors and accuracy of the path planning (SLAM) functions.

Figure 13.12: Photo of the mission environment with the RAS during run-time on route to enter the confined space.
To demonstrate autonomous confined space asset integrity inspection and how the SDA services symbiotic collaboration across the cyber-physical elements (robotic platform, sensors, reliability ontology and the DT) readers are encouraged to view the videos available through Mitchell et al. [118–120].

An autonomous inspection mission can be divided into eight phases, with each phase having distinct objectives. They are:

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

Three major system issues were generated on the CPS to simulate symbiotic collaboration dynamics. This would ensure the assessment of whether the RAS reassess the mission symbiotically via intra-inter system certification and adhere to rules which ensure their safety during a mission. The autonomous mission evaluation aimed to demonstrate ‘Adapt and Survive’ where the run-time and dynamic conditions imposed on the CPS enable the AI-assisted ontology to diagnose a fault and ensure the correct decision is made or fed to the human operator via the DT. This ensures commensalistic collaboration with the designed reliability ontology to ensure the robot can complete the following:

- Detect hazards or obstacles to accomplishing the mission via on-board sensing.  
- Detect risks or obstructions to ensure safety of the RAS within the surrounding environment and nearby human presence detection via integrated sensing mechanisms.  
- Support real-time C³ with the DT to pass on obtained asset integrity management data and advise the human operator and other robotic systems and software packages during run-time via knowledge sharing which is enhances via bidirectional communications.  
- Trusted autonomy and corroborated decision making via low latency, wireless communications through both the AI and/or the human operator.

A significant component of this case study is to display resilience and reliability during autonomous operations whilst maintaining a mission envelope within safety compliance. Success is created through C³ in the SSOSA methodology to provide collaborative governance between the systems that enable the robot to operate safely and autonomously and provide an increased awareness for a remote human operator.

The run-time reliability ontology enabled symbiotic assessment of the RAS for certification of its own systems where in the case of potential significant deterioration, the mission could be autonomously terminated. Each autonomous mission aspect was evaluated and in this section, we focus on the robustness and resilience of the robotic platform and its run-time reliability ontology. The mission plan is illustrated in Fig. 13.13, highlighting the main stages of the asset integrity inspection and induced faults on the robotic platform. The applied methodology is presented within Fig. 13.17 and
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displays the operations, symbiotic decisions, and interactions between systems. The resulting flow chart is discussed throughout the following subsections.

A. Pre-Mission Planning

An essential event to ensure a safe mission includes pre-planning. Reconnaissance is first conducted to map the mission area to establish the working environment. Cyber-physical sensing is provided by both 2D and 3D LiDAR to assist the human operator to navigate the autonomous system around the infrastructure and environment for the creation of a map which can then have waypoints assigned to it (Fig. 13.14). Therefore, under COVID-19 requirements, personnel do not have to be on-site to complete the autonomous missions. The cooperation between robot and human operators establishes low obstacles and raised surfaces such as pipework. A schematic displays the resulting reconnaissance map layered on the 3D model as in Fig. 13.13. For asset integrity inspection of corrosion, the FMCW radar was used.

For the autonomous mission evaluation, the Robotic Operating Software (ROS) planning and navigation stack was implemented on-board the autonomous system.

To achieve the assigned objectives of the autonomous mission, the robotic platform acted upon tasks assigned to it by the human operator. The decision making in these tasks was based on PDDL associated relational sequential system actions [121]. This represents the future remote working conditions as engineers can access missions remotely in a COVID-19 climate. Waypoint goals are positioned and received at the navigation stack from the planner. Simultaneous Location and Mapping (SLAM) is used for the navigation. A DT provided both graphical interface and dashboard for the operator/planner to create the waypoints. The integration of computation, data and process analysis ensures the selected robotic platform can complete the required mission. From the point of the mission being initiated, the RAS actively certifies its on-board systems. This is achieved through watchdog nodes, which are subscribed to fault and warning diagnostic data from the robotic platform ontology.
B. Mission Start at Baseline

The autonomous system will remain inactive at an authorized home position until the robot is initiated by the human-in-the-loop. A resilient wireless connection is required between the DT and CPS to ensure mission start. Intra-system corroboration is achieved by the system continuously self-certifying its systems from the mission start. This network is a central feature of cyber-physical systems that ensures the human operator has an overview that the robot is fully deployable and operational. Watchdog nodes have been implemented to provide another level of autonomous self-certification. The most efficient routes are calculated by the autonomous navigation and mapping systems.

C. Transit to Asset Integrity Scan 1

A low-level path planner is utilized in conjunction with SLAM for transit to the first waypoint. The costmap represents the map generated to ensure collision avoidance and path planning between waypoints is achieved; this is created from the onboard LiDAR sensors (Fig. 13.15). The PDDL produces a waypoint action including x, y and \( \theta \) locations and are utilized for autonomous navigation by feeding this information to the ROS move_base.
Figure 13.15: A local costmap emphasising waypoint positions set by the human operator and the possible routes for the robot to complete.

D. Perform Asset Integrity Scan 1
For this pilot, the K-Band FMCW radar sensor was utilized as a non-contact asset integrity inspection method for the detection of corrosion. The challenge for this inspection pertains to the safe manoeuvre of the robot and the FMCW payload whilst avoiding collisions with infrastructure. The CPS provides information to the remote human observer with data from the physical environmental sensing to the DT to ensure C³.

E. Transit to Asset Integrity Scan 2
The transition to the second asset integrity inspection begins the confined space mission. The infrastructure has a narrow corridor and a space with minimal room for manoeuvrability of the robot. To ensure accurate manoeuvrability, autonomous navigation of the confined space was setup through the motion planner. Maintaining the ability to avoid collisions allowed the robot to adapt with the dynamic mission space where personnel could be within the workspace for certain areas. This ensured a safe mission envelope.

F. Perform Asset Integrity Scan 2
At this point, the second waypoint has been reached by the autonomous system. The system is now ready to carry out the second asset integrity inspection for corrosion precursors. The parameters of this inspection are comparable to the first inspection highlighted in stage D.

G. Return to Base Point
Upon the return to the base point, three faults were induced via simulation on-board the autonomous system through code which was initiated within the robotic platforms
hardware on this phase of the mission. The fault severity levels increase upon each induced fault.

The goal of the run-time reliability ontology is to discover or detect invalidities or anomalies within the autonomous system whilst it operates and under stress. This system can corroborate the CPS behaviour relative to the required specifications and ensure performance is as expected.

Several semi-automated mission envelopes were implemented in the confined space asset integrity inspection including:

- A potential warning or fault within an element which is not sensed, for example, a tyre failure.
- A low battery voltage prediction.
- Root cause evaluation for a third module affected by a failure in a pair of other modules.
- Predictions for elevated temperature within the driver of the motor.

The implementation of the ontology prioritizes fault thresholds over warning thresholds (Fig. 13.17G) in all instances to safeguard the reliability of the CPS. Figure 13.17G represents the final stage of the autonomous mission where the methodology of the decision making is displayed to highlight the connections of the SSOSA across systems within the architecture.

The remote operator is notified of the mission status in real-time though the DT with a precise estimation of the system status via diagnosis and prognosis. This ensures a SSOSA due to the systems engineering from the SDA to ensure the resilience of the platform and allow the remote operator to have an operational overview of the robotic platform.

H. Mission End

This case study of an autonomous mission evaluation demonstrates the advantages of a real-time reliability ontology. The induced warning indications were accurately detected by the run-time reliability ontology as expected alongside the anticipated decisions as designed within the ontology. These warnings allow the operator to make decisions as to terminate or continue the mission and is another layer of protection and interaction for the human-in-the-loop. To ensure obedience to the safety rules, the robot would still continuously evaluate its capacity to function efficiently after each subsequent warning, ensuring the survivability of the RAS. From the perspective of symbiosis, the DT serves to corroborate human-in-the-loop actions with respect to real-time mission status and fault prognosis. The twin presents representation and descriptions of data, which is transformed into selected ontology updates. These updates are presented as human readable text describing hardware and system faults and warnings. A red colour is used on the text to highlight the presence of a warning or fault. In the evaluation of the autonomous mission discussed in pilot study, a watchdog node linked to oversee battery state of health alerts detected a low battery fault. The fault during the autonomous mission evaluation is pictured as in the DT within Fig. 13.16, where the system was created to ensure the human operator is aware of all red high ranked alerts. The DT also describes operating information and diagnostic information including battery status and motor parameters. The integration, decision making and coordination of all system subcomponents and operator objectives are achieved via collaborative governance as within the SSOSA.
The motor temperature symbiotic safety compliance modes of the RAS are presented in the taxonomy structure in Table 13.4. This identifies the levels of safety compliance modes corresponding to the collaborative governance aspects of operation, provision, and outcome and system awareness corresponding to the following relationships: Mutualism, Commensalism and Parasitism (MCP). MCP is critical for the SSOSA for the creation of exchanges across or between the autonomous systems (DT, ontology, robotic platform) and operator. The capability for the CPS to create system awareness enables the RAS to monitor self-preservation without disturbing the human operator unless necessary. In this case, although the mission could be terminated by the human operator, self-certification ensures the integrity of the robotic platform. Mutualism is moderate whereas parasitism is low, and commensalism is high in the mission envelope as the autonomous system continues with its list of objectives with a low chance of adverse consequences to state of health of the RAS system.

**Table 13.4:** Taxonomy of symbiosis to achieve safety compliance and autonomous systems temperature of the motors

<table>
<thead>
<tr>
<th>Collaborative governance (C³)</th>
<th>Safety compliance modes</th>
<th>Mutualism</th>
<th>Commenalism</th>
<th>Parasitism</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Awareness</td>
<td>Moderate</td>
<td>High</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Human-in-the-loop Provision</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Operation</td>
<td>Self-certification (Implication)</td>
<td>Augmentation (Causality)</td>
<td>Instructional (Prevention)</td>
<td></td>
</tr>
<tr>
<td>Outcome</td>
<td>Positive Anticipation</td>
<td>Indeterminacy</td>
<td>Negative Anticipation</td>
<td></td>
</tr>
</tbody>
</table>
Human miscalculations are reduced within a mission due to the implementation of run-time reliability ontology. Under human-in-the-loop provision as in Table 13.4, Parasitism is low as fault thresholds for all problems that may risk the integrity of the
RAS are established such that the system automatically ceases all operations of the real-world robot if any hazardous operational conditions are discovered. Mutualism exists due to the SSOSA due to knowledge shared throughout systems which could previously not have been feasible without the augmentation of subcomponents at both data and information levels. For this example, the human operator is updated via warning messages (information), and a new threshold for fault detection (data) is triggered which causes an emergency mission stop. Commensalism and parasitism includes a balance between the alteration of fault and warning thresholds which should be minimized during the planning phase. To minimize parasitism, an experienced operator should only alter the thresholds. If they are altered too leniently/inappropriately, deterioration of the robotic platform (host) could occur resulting in a benefit for the human operator (symbiont). This results in the priority of the mission at the detriment of the robot. Commensalism is achieved when faults are adjusted by a proficient operator. This results in a mission termination, in the case the risk the thresholds present have a minimal impact on the mission. This is corroborated by the reliability ontology. The robot can therefore still complete its mission where there is a benefit to the human due to the increased safety of the robot or less restrictions on performance, hence commensalistic. However, there is a fine line between commensalism and parasitism in this scenario when altering ontology warnings and faults. Therefore, an experienced and trained operator should be certified to do this to ensure the safe operation of robot over the mission priorities.

5.2 Digital Twin

A DT is identified as “digital replications of living as well as non-living entities that enable data to be seamlessly transmitted between the physical and virtual worlds” [51]. A “stage 4” DT was utilized within this work with extensive simulation abilities and data analytics, in particular influencing edge-processing during run-time for the prediction of forthcoming behaviours (Fig. 13.18). Positive interdependencies across external and internal functions of the DT allow the combination of run-time processes from sensors and payloads with operational AI services. Legitimacy is supported within and between existing technologies by following this paradigm.

5.2.1 Ghosting Function for Dual Manipulators

The creation of run-time evaluation and collaborative functions of the robotic arm manipulators was achieved via the DT interface, allowing for the user to observe and command the manipulator operations onboard the robotic platform during run-time. The reliability ontology can generate messages and are displayed in a similar manner to as previously discussed in Fig. 13.16 where the user can intuitively command the arms on the CPS to mirror their real-world condition in real-time. Run-time connectivity between the client machines and robot is achieved via a DT server package which is utilised onboard the ROS core of the robotic platform. A key advantage of the DT discussed includes the interchangeability between operating devices as the user is not tied to using a ROS based system. The SDA allows the user to connect to the DT via a mobile, tablet, MR device or standard laptop from anywhere whilst remote to the CPS. The Graphical User Interface (GUI) of the DT offers the visualization and interaction required to demonstrate the SSOSA for manipulation of processes. Run-time prognostics verify the significance of the implementation of bidirectional
interaction and communications. This is enabled by a physics-based operational view, which encourages trustworthy interactions with the DT and system health status via C³ governance.

The synchronized robotic platform in the real-world and DT is displayed within Fig. 13.19. The ROS core provides the data necessary for the DT to position the robotic arms to reflect the real-world platform. Synchronization of all system parameters is achieved upon mission start, which is maintained for the duration of the mission.

The preview function integrated in the DT allows the remote human operator to plan and control the manipulators as displayed in Fig. 13.20. Planned positions and trajectories of the arms are rendered as translucent ‘ghost’ models. This allows the operator to preview and analyse the requested operations. The use of sliders within the DT GUI enables intuitive control of the ‘ghost’ manipulator arms by simulating each axis of the manipulators. This allows for verification of safe robotic arm motions via simulations for remote operators, before executing the movements to the field robotic platform. This increases the trust levels for the human that the manipulators will operate as planned.
Figure 13.19: Left: Robotic arm as displayed in the DT. Right: Synchronized with the real-world robotic arm during the mission.

Figure 13.20: Meta ghosting function of the robotic arms within the DT, displaying the desired trajectories of the arms. Also displayed are the axis controls within the user interface.

Run-time fault prognosis was also evaluated within the DT. Figure 13.21 shows a scenario in which a motor fault is induced upon the robotic arm within the ROS core. The location of this fault is shown in the DT by colour coding the arms red (Fig. 13.21). Colour coding in this manner allows for the rapid identification of an arm which has a diagnosed fault.

5.3 Mixed and Augmented Reality

Utilising MR and AR devices, such as the Microsoft HoloLens, allows for prompt evaluation of the health status or a RAS, whether the operator is on-site or working remotely. The AR interface presented in Fig. 13.22 highlights the health status where
Figure 13.21: Meta warning function of the DT. Arms are colour coded, with a colour change showing a motor fault.

Figure 13.22: QR codes are recognized by an MR device and enable human-readable health status information to be overlaid on the robotic platform.

natural language indicates the RAS state of health using the information from a Quick Response (QR) code. The colour coding as presented in Fig. 13.23 highlights the health status of the component within the autonomous system. In this scenario, the base is depicted red to enable rapid visualization of a fault when viewed through the headset. Customization of the displayed colour coding is possible to reflect different systems and fault types.
Figure 13.23: A demonstration of a defect warning within the AR interface. Top: Live diagnostics of the robotic platform. Bottom: Colour coded defect warning displayed upon detection of defect within the robotic platform.

6. FMCW Radar Sensing for Integrated Offshore Environmental Sensing

6.1 Asset Integrity Inspection

Sensing with Frequency Modulated Continuous Wave (FMCW) is reliant on the interaction of transmitted microwave radiation with a material. The properties of the reflecting surface can be obtained from analysis of the reflected electromagnetic (EM) wave, which are a result of the scattering, emission, absorption and phase change, and are unique to the reflecting object. Microwave sensing offers rapid measurements for edge analytics, high resilience to ambient environmental conditions and non-invasive evaluation of materials. The hardware is low power and a solid-state electronic device which is certified as ATEX compliant. Millimetre-wave radar technology, in both the X and K bands, have tuneable EM outputs and have proven harsh environment capability, which include high temperature or high pressure operating conditions [122–130]. In addition to having the capability to operate resiliently in opaque conditions, such as mist, fog, smoke and dust.

This case study demonstrates the capability of the FMCW system for asset integrity inspection and was utilized as a run-time device on the deployed CPS, a Husky autonomous ground vehicle [131]. The demonstration of the sensor in this role returned critical asset integrity information in real-time to our DT and represented the
inspection of an asset in a simulated offshore environment. We discuss in detail the successful deployment of two use cases: corrosion inspection on steel infrastructure targets and integrity monitoring for wind turbine blades via a specially developed Asset Integrity Dashboard (AID). The FMCW sensor was utilized for both mission profiles. The implementation of this inspection device further advances the SSOSA, where information was relayed to the DT and represented to achieve C³ governance.

Improved manoeuvrability of the FMCW radar sensor for asset inspection was achieved via the gripping of the sensor as a payload within one of the dual UR5 robotic arms, as pictured in Fig. 13.24, allowing raster scanning motions for a wide area of fault assessment, while the other robotic arm may be used for manipulation and asset intervention manoeuvres.

![Dual UR5 husky A200 with the FMCW millimetre-wave sensor in the gripper during a corrosion inspection.](image)

**Figure 13.24:** Dual UR5 husky A200 with the FMCW millimetre-wave sensor in the gripper during a corrosion inspection.

### 6.1.1 Structural Corrosion

Steel structures in the offshore environment are prone to surface corrosion, reducing the operational lifetime of the infrastructure. The quantification and detection of corrosion on the surface of structures is therefore essential to ensure efficient and effective O&M schedules [132]. The robotic platform was used during an integrity inspection of the steel sheet for corrosion and is pictured in Fig. 13.24. The observed reflected wave amplitude response for different concrete and metallic targets, at a consistent sensor-target separation of 10 cm, are shown in Fig. 13.25. Distinct contrasts in the return signal amplitude are observed for the lightly corroded and non-corroded steel sheets, in addition to substantial differences when comparing the polished aluminium and different areas of the concrete floor.
Figure 13.25: Reflected wave amplitude responses observed for multiple concrete and metal targets. The peaks observed at bin 9 represent the targets responses at 10 cm from the sensor tip.

A DT facilitates a remote perspective for asset health management and customized O&M scheduling as data from an inspection device can be fed to the DT, where the human operator gains an increased understanding of the asset. This allows for an enhancement of C³ with an increase in corroborative compliance, as the data from the inspection device can be viewed in the synthetic environment alongside historical data and past decisions on maintenance.

6.1.2 Wind Turbine Blades and the Asset Integrity Dashboard

Wind turbine blade defects can be categorized into distinctive types, as detailed in Table 13.5. This includes delamination, water ingress and cracking. The use of high-resolution cameras via UAV platforms (visual and infrared) represents current state-of-the-art in the inspection of wind turbine blades and requires post-processing from experts to identify/infer regions with notable damage. The FMCW radar sensor may be deployed as a handheld device or as part of a robotic platform mounted wider sensor suite. This subsection presents the FMCW radar sensor for inspection of a wind turbine blade removed from operations, exhibiting an internal delamination defect (type four), where the defect is situated within the structure of the blade, as displayed in Fig. 13.26A, and where the FMCW radar was positioned external to the blade facing the target as illustrated in Fig. 13.26B. The technology evaluates the ability for the millimetre-wave sensor to detect defects which can accelerate asset degradation in adverse weather conditions. The subsurface faults within the wind turbine blade used for this study are highlighted in the Asset Integrity Dashboard (AID), as displayed in Fig. 13.27. A remote operator can access key information from the offshore inspection via interaction with the synthetic. Colour coding aids easy identification of faults, with green representing a healthy baseline area and red identifying an area of the blade containing a defect. Interaction is achieved by clicking on the defective area, revealing layered information blocks for the user to interrogate. Within the synthetic
environment, the operator can view further information, including graphs of the radar response, which is displayed within Fig. 13.27 within the AID tool but also as a clearer illustration in Fig. 13.28. The graph displays the FMCW response to the following:

- An undamaged baseline area of the wind turbine blade structure.
- A type four delamination defect
- The inclusion of 3 millilitres of fresh water within the same type four defect at 3 minutes and 40 seconds into the experiment duration.

A summary video presented by Mitchell et al. [133], highlights the interaction between the layers of the AID.

### Table 13.5: Wind turbine blade failure modes listed by description [111]

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Adhesive layer failure and growth in the bond joining external structure and main spar flangers (debonding)</td>
</tr>
<tr>
<td>2.</td>
<td>Adhesive layer failure in the external structure along leading/trailing edges (adhesive or joint failure)</td>
</tr>
<tr>
<td>3.</td>
<td>Failure at the interface between external and core sandwich panels in external structure and main spar</td>
</tr>
<tr>
<td>4.</td>
<td>Internal failure and growth in laminated structures comprising skin and/or main spar flanges, under tensile or compressive loading</td>
</tr>
<tr>
<td>5.</td>
<td>Laminated external structure and main spar debonding of fibres (fibre failure in tensile load conditions; laminate failure in compressive loading conditions)</td>
</tr>
<tr>
<td>6.</td>
<td>Buckling of external laminated structure due to debonding and growth in the external structure and main spar bond under compressive load</td>
</tr>
<tr>
<td>7.</td>
<td>Formation and growth of cracks in the external protective layering resulting in detachment of the gel-coat from the laminated external structure</td>
</tr>
</tbody>
</table>

Figure 13.26: A – Wind turbine blade section end elevation view highlighting the internal delamination defect. B – Elevation view of the wind turbine blade section detailing the external inspection area.
Figure 13.27: AID indicating the synthetic environment of the sandwich composite blade, where a cross indicates a defective area, while providing a human operator with options to view or extract detailed fault information.

Figure 13.28: Observed signal return amplitude of 3 ml water added within an area of internal delamination.

An improvement of $C^3$ is generated from the AID post-processing tool via data collected from the FMCW sensor. This helps wind farm operators to gain an operational overview of O&M data collected from the real-world asset, leading to easy detection and localization of problems which occur on wind turbine blade structures.
This application demonstrates the capabilities of millimetre-wave radar sensing, via the edge analysis of non-destructive evaluation sensors in the offshore environment, and their role in the wider integration of data to DTs via robotic deployment. This integration capability also extends to foresight monitoring for RAS to ensure safety compliance and trust.

### 6.2 Foresight Monitoring of Safety and Mission Environment Conditions

Service robots are intended to be deployed in difficult situations, which include hazardous and complex scenarios, such as visually opaque and GPS denied areas with restricted communications. To overcome these challenges, the use of accurate sensors and payloads are crucial for RAS to ensure they can ‘Adapt and Survive’ by having the capability to assess a scenario rapidly and effectively. Sensors must therefore have extended capabilities to localize infrastructure and environment (current state-of-the-art such as LiDAR), but also to identify differing types of surface condition, materials and variables that affect external mapping, such as the detection of hazards through solid, low to medium dielectric structures, such as walls (future state-of-the-art capabilities). This allows safety precautions to be followed by a robotic platform for a range of surface conditions, or if an engineer enters the same workspace.

Humans can rapidly lose trust in RAS if a major fault occurs in a system, CPS enables assurance due to the data-driven approach. Regulators require defence in-depth, resulting in trusted autonomous services and a high level of foresight in autonomy, alertness with intervention strategies to mitigate unanticipated threats to the CPS, ensuring health and safety requirements are preserved. Within the SSOSA, the FMCW radar sensor ensures that foresight monitoring ensures safety governance. Due to this approach, risks are reduced in the operation of AS around humans as humans can be detected when deployed offshore. This leads to an increase in C3, allowing RAS to action decision making at an earlier stage, depending on the scenario.

### 6.2.1 Surface and Waypoint Condition Analysis

Inherent risks are associated with the surface of the ground which autonomous vehicles will have to overcome. The FMCW radar sensor enables non-contact monitoring and analysis of surface waypoints, ensuring compliance to safety requirements and to prevent failure in areas where surface ice, oil are present or are unstable. This capability forewarns a wheeled robot or vehicle of areas which have less traction. The millimetre-wave sensor was tested on a section of hot rolled asphalt, following the application of a brown salt brine solution at an ambient laboratory temperature of 24.8°C. The peak interfacial reflection at 10 cm from the sensor was extracted via fast Fourier transform (FFT) from time-domain data and is displayed within Fig. 13. Iterative applications of brown salt brine solution of 20% weight by volume were then placed in the field of view of the radar sensor, where a sufficient duration of time was allowed for the solution to fully evaporate before reapplying the same volume (30 ml/m²) and concentration of salt solution. Residual salt in the field of view was seen to accumulate during the four applications of brine. The brine solution concentration was mixed to the same standards stipulated for highway maintenance during winter operating conditions between –7 and –10°C [134–136]. The deposition of the initial brine solution provides a return signal baseline. The subsequent applications show
increases in amplitude response, which are consistent with the presence of increased residual salt following the deposition of the previous brine solution within the sensor field of view. The observed deterioration in signal response over time links to the evaporation of water content in the brine solution, leaving residual salt levels incrementally higher than the previous application [137].

Symbiosis between an environment and robotic platform improves as a robotic platform could scan nearby waypoints to assess the terrain conditions on a given route. This information would then be relayed to a DT and distributed between local robots to ensure paths are planned to avoid areas which are unstable or with traction issues that could impede or harm the mobility of the robotic platform. This symbiosis would represent multi-platform mutualism in a fleet of autonomous ground vehicles acting in unison.

6.2.2 Safety in Low Visibility or Opaque Environments

When deploying RAS, two key factors for consideration are resilience and safety compliance. Autonomous systems are created for deployment in dangerous situations, such as opaque or severely restricted visual conditions. Limitations in state-of-the-art sensing, such as LiDAR etc., mean that robots experience difficulty navigating in areas where steam, smoke, or misty conditions are prevalent. Therefore, systems solely reliant on visual spectrum sensors lack the resilience to operate fully autonomously in the oil and gas sector, offshore renewable energy sector, search and rescue or mining sectors. RAS requires supporting or secondary navigational payloads which can guarantee the robustness of operations during a mission to ensure that an ‘Adapt and Survive’ framework provides the required safety of the resource, as outlined in the SSOSA.

The FMCW payload is a critical and promising radar sensor to ensure the resilience of robotics in challenging operational conditions. The following subsections
The Future Workplace: A Symbiotic System of Systems Environment

present the application of the FMCW to detect and distinguish humans within shared workspaces and to ensure a robot can comply with safety procedures and rules via low to medium dielectric detection of human targets through walls or doors.

6.3 Human Proximity Alerting

The investigation of human proximity alerting took place in the following evaluation. This enabled the autonomous platform to detect and distinguish between a human and an autonomous system or structure. This demonstrates improvements in the situational awareness of the platform, which ensures safe robot proximity to infrastructure and humans in adherence to safety compliance requirements. This represents a significant enhancement of SLAM in the presence of humans, where safety compliance is maintained via C³ governance. This application summarizes the utilization of the millimetre-wave sensors to differentiate between a human and a metallic target over a range sensor to target distances. Figure 13.30 shows the FMCW amplitude response for both targets as a function of range.

![Figure 13.30: Return signal amplitude versus distance for human and metal sheet targets.](image)

The human test subject was positioned in the centre of the sensor field of view and moved from 1 metre to 4 metres from the sensor in one-metre increments. This procedure was repeated for the aluminium metal sheet, which measured 700 mm by 500 mm. Relevant annotations have been made to Fig. 13.30 to more effectively present the findings from the data collected. The diagram firstly presents an empty reference signal via the solid blue line and blue rectangular block at 6.5 m for when no objects are in the field of view of the antenna. The metal sheet has been represented in the diagram via yellow blocks and solid lines, where humans are represented as human silhouettes and dashed lines. The results shown indicate a clear contrast in the return signal amplitude of a human when compared to a metal sheet. The peaks collected within the data were passed through an algorithm to calculate the reflection magnitude relative to the set baseline, which was taken to be the laboratory wall at 6 metres from the sensor. The calculated reflection magnitudes are presented in Table 13.6 [138]. Note: the distance calculated does not account for the length of the waveguide, resulting in target distances increased by 0.5 metres, as shown in Fig.
The application of the FMCW radar sensor for human detection results in increased symbiosis between a robotic platform and its environment.

### Table 13.6: Calculated reflection magnitudes for contrast identification between aluminium sheet and human targets

<table>
<thead>
<tr>
<th>Target type and distance from sensor</th>
<th>Relative magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>“No Target” Reference (or Lab Wall at 600 cm)</td>
<td>1</td>
</tr>
<tr>
<td>Human at 100 cm</td>
<td>1.54709657</td>
</tr>
<tr>
<td>Human at 200 cm</td>
<td>1.875306979</td>
</tr>
<tr>
<td>Human at 300 cm</td>
<td>1.519923948</td>
</tr>
<tr>
<td>Human at 400 cm</td>
<td>1.322427315</td>
</tr>
<tr>
<td>Aluminium Sheet at 100 cm</td>
<td>14.92893924</td>
</tr>
<tr>
<td>Aluminium Sheet at 200 cm</td>
<td>10.79030341</td>
</tr>
<tr>
<td>Aluminium Sheet at 300 cm</td>
<td>7.516517468</td>
</tr>
<tr>
<td>Aluminium Sheet at 400 cm</td>
<td>13.51913174</td>
</tr>
</tbody>
</table>

### 6.3.1 Through-wall Detection

This case study investigates the unique application of the FMCW radar for through-wall detection of a target. The challenge addressed by this work is whether the FMCW sensor can improve the operational awareness of a RAS to signal contrasts which indicate whether a human or robot has entered the mission space or is blocking a doorway, while unseen from the other side of that doorway or wall. Constricted high foot-traffic areas would benefit from this type of situational assessment mapping, as it promotes enhanced safety compliance of the CPS. A specific example is where a human is in close proximity to a door, through which a robot requires passage. If the robot unknowingly operates the door in close proximity to the human, this could result in an accident. Therefore, if the FMCW radar was employed, the radar could detect the human whilst obscured by the door and advise the robot to utilize another entry door. This increases the safety compliance by reducing the chance for collisions to occur during transit through doors and avoiding getting stranding between doors which would render it unusable.

An illustration, where the sensor was situated 10 cm from a partition wall within the laboratory, is presented in Fig. 13.31. The human test subject held a 30 × 30 cm copper sheet on the far side of the concrete partition wall. Consequently, the copper sheet was completely obscured from the sensor by the partition wall during this test. The copper sheet was then moved from position A to position D whilst the radar continuously scanned. The results are displayed in Fig. 13.32, where an empty reference baseline was taken, represented by the space between the wall 1 and wall 2. The human test subject positioned their back to wall 2, while holding the copper sheet in the field of view of the sensor. This correlates to Position A (solid black peak). As the human test subject and copper sheet advanced towards wall 1, peaks are observed at Position B (solid grey peak), Position C (dashed black peak) and Position D (dashed grey peak). Each peak represents the return signal amplitude from the interface of the copper sheet to the radar. This is represented as a distance to the target.
Robotic manipulator arms represent “ground-up” technology and are progressively being used to operate entrance/access points autonomously. The Boston Dynamics SPOT Arm [139] has an inbuilt LED and 4K camera, which can be used for inspection, however, the arm has no mechanism to detect key contrasts through a door. Therefore, if the arm were to push a door, this could result in an injury to a human in close proximity to that door or if an unseen object was leaning against the door. This represents a new challenge in the safe transition of robots into unmapped workspaces. Current autonomous systems are not required to assess whether areas beyond obstructions are clear, such as behind a doorway. This is due to the limits imposed by current, visual spectrum SLAM systems. The application of FMCW radar in this role facilitates improvements in safe operating procedure when a robot is required to pass through visually opaque doors. Symbiosis is accomplished via commensalism as the robotic platform can interact with the human or obstruction without the need to inform the human.
6.4 Search and Rescue

Search and rescue environments are often represented as harsh and highly variable conditions, often with extreme thermal contrasts, low visibility, constrained spaces, noxious fumes combined with the threat of significant infrastructural failures. These are often major contributing factors in human disorientation. In the previous subsections, we discussed the capability of the FMCW sensor to detect static and dynamic measurands for human detection through walls in the built environment. The FMCW system evaluated within this chapter has demonstrated operational proficiency when in environments known to cause severe impediments to conventional SLAM technologies, including LiDAR systems and visual or thermal spectrum imaging.

We identify applications where millimetre-wave sensing may be further developed to improve symbiotic relationships across systems used for search and rescue. These are:

1. Differentiation between infrastructure and humans, allowing for the implementation of vital rescue strategies in zones where standard communications are rendered ineffective, such as obstructive terrain, GPS-constrained locations, and situations with communications dead zones.
2. Detection of humans obscured by collapsed infrastructure or in low visibility situations within a search and rescue mission area, including opaque or extreme environments.
3. Detection of crucial vital signs for rapid review of casualties [140–143] and real-time communication of casualty data to medical facilities.
4. Accurate real-time situational reporting and incident area mapping to support navigation of dynamic disaster areas.

7. A Systems Approach to Real-World Deployment of Industrial Internet of Things

Deploying CPS’s, specifically, sensors in a real industrial setting are often hampered by unpredictable challenges that are not encountered in a controlled environment. Using a bottom-up systems approach to identify, integrate, and install an IIoT system, the challenges can be mitigated [144].

7.1 Challenges in IIoT Deployment

Every industrial site has a set of unique challenges; however, the majority of these will be the same across sites and sectors.

1. Current IIoT systems are often inflexible in their data acquisition which can prove difficult to adapt to the range of industrial sites they are required for.
2. Industrial sites are dynamic, they go through periods of upgrades and repairs, and the IIoT systems are required to be robust enough to handle these upheavals.
3. Network connectivity can vary unpredictably on industrial sites, whether this is due to wireless communication being protected with firewall systems, the range of materials used to construct such site blocking wireless signals or the distance a signal is required to cover.
7.1.1 Bottom-up Approach

**Step (1) High-Level Abstraction:** Identify the critical assets, then assign them to two classes:

a. Class-1: Passive Assets (e.g., crates, walkways, and walls)
b. Class-2: Active Assets (e.g., power generators, wastepipes, air conditioners)

The aforementioned generalization is essential as in order to be able to apply the bottom-up approach in a generic way to other situations which share a set of common features.

Class-1 assets do not generate continual vibrations or high-frequency movements, while Class-2 assets do. The measurements gathered from the assets via the sensors need to be transmitted to a central repository stationed in a secure location. A secure area was created with the receiver and edge equipment, allowing for the readings from each of the asset’s sensors to be stored. If the asset is within a close proximity to the secure location (sub 100 m), Bluetooth, Zigbee, and Wi-Fi can be employed. If the asset is located further than 100 m, either LoRa (Long Range) [145] or Long-Term Evolution (LTE) is required. If communicating using LoRa an area ideally with a line of sight to the sensor platforms or assets to be monitored should be setup as LoRa signal quality is greatly reduced by obstructions.

Often the assets that are of interest are remotely located, and thus the battery life of the CPS should be in the order of months to years in length. LoRa provides a method of long-distance communication and which has a lower power requirement than other wireless methods of communication. However, it has bandwidth restrictions and cannot be deployed where high-sample and communication rates are required.

Because Class-1 assets do not generate high-frequency measurements, each asset is ideal for using LoRa as its mode of communication. However, with Class-2, assets are more varied and thus, so are the required communication methods. Additionally, the assets surface materials determine how the unit can be mounted, which can also be configured into the asset description.

**Step (2) Module Selection:** Typically, an IIoT system consists of multiple discrete active and passive elements such as sensors, communication devices, batteries, encapsulations, etc. The Step (1) classification determines the modules to be used. For example, a Class-2 could use a Hall effect sensor to record its magnetic field, determining the communication module needed.

7.2 System Components

7.2.1 Sensing Platform

To monitor the structures at this industrial site, the Limpet platform [55] was deployed. Every Limpet has an array of sensors that include optical, temperature, sound, magnetic field, distance, pressure, humidity, and IMU. ROS is integrated into each Limpet, allowing joint operations with a broad range of robotic systems. As the assets to be monitored were spread over an expansive area (over 100 m), LoRaWAN was used to overcome the range and power issues.

To enable the Limpet to take advantage of the extended range of LoRaWAN, a LoPy4 expansion board was added. As offshore platforms are the desired environment for the Limpet to be deployed, data security is essential. Therefore, a local LoRaWAN
communication system was deployed. Deploying such a communication system also removes any reliance on existing or commercial communication connectivity.

The local communications system integrates the LoRa Server project developed by CableLabs [145]. The Limpet transmits its sensor data over a UART connection to the LoPy [146], then data packets are transmitted to the securely located data hub via the LoRaWAN wireless protocol. To provide an adequate power supply for the deployment duration, a 5 V lithium polymer battery was integrated with the Limpet. To allow a concise reference to the complete system, each combination of Limpet, LoPy, and a battery is designated an L-node. Figure 13.33 shows a complete L-node.

![Figure 13.33: The Limpet V1, (A) The LoPyBoard and antenna, (B) Limpet V1 mounted on the LoPy expansion board connected to a rechargeable battery, (C) External antenna hole and watertight O-ring, (D) Complete Limpet V1 encapsulation [144].](image)

The Limpet is both required to be able to adhere reliably to multiple surfaces and to withstand harsh environmental conditions. For this reason, the outer encapsulation is 3D printed with an infill of 95% in Polylactic acid before a coat of acrylic spray paint is applied, followed by an epoxy sealant, all gaps are compressed sealed with O-rings. During lab tests, the encapsulation achieved the targeted level of IP54 rating [147]. The adhesion for the Limpet came from an arrangement of five to six neodymium magnets arranged as required for the surface it was fitted to or via a steel strap.

### 7.3 Data Acquisition, Visualization, and Querying

#### 7.3.1 Data Acquisition

The L-nodes were installed at distances up to 100 m away from the secure area. As LoRaWAN was the predominant method of communication, the data hub system
The Future Workplace: A Symbiotic System of Systems Environment

was composed of a Sentrius™ RG1xx series LoRa-Enabled gateway from Laird™, a NETGEAR® Nighthawk R7000 Wi-Fi router, and an Intel® NUC.

The gateway operates a packet-forwarder software that forwards the incoming packets to a network server via a User Datagram Protocol (UDP). The LoRa gateway and network server are given IP addresses by a local Domain Name System (DNS) server. Typically, an IIoT generates a constant stream of data, in prestigious amounts and in an unstructured format. Relational database methods are the standard in data storage for many applications. However, they are deemed inadequate for IIoT applications due to the restrictive computational rates and steep storage expansion costs [20]. Therefore, MongoDB, a NoSQL (Not only SQL) database, was used to store the data received from the sensor nodes. Creating the optimal schema for the deployment scenario is fundamental for future scalability. A schema is away the unstructured data is sorted in the database. Each L-node was sending data every five seconds, an average of 12 data packets per minute during this scenario. The data schema wrote 720 packets to a single document over an hour. This schema has a considerably fewer number of reads than one that writes a separate document for every data packet received. As large amounts of data queries are expected of an IIoT system, the optimization of the read rate is crucial, especially for high scalability.

7.3.2 Data Query and Visualization

The primary purpose of data aggregation is the smooth retrieval and visualization of critical information. A dashboard-with-query processing engine that visualized the status of the sensors for the L-node chosen was created. As the dashboard is limited and only able to illustrate a finite amount of information, it incorporated a drop-down interface to question previously recorded data. The dashboard-with-query engine was created using a Python library called Dash running as a service app. The app was hosted on the data hub and could be viewed via a secure URL. ngrok7 was used [148].

7.4 On-Site Deployment

The data acquisition system was deployed alongside the L-node in locations visible in Fig. 13. Each L-node was placed on a different type of machinery or infrastructure within the LoRa’s range and had the required line of sight to guarantee optimal LoRa data transmission. Across the whole site and on multiple different types of asset, a total of seven L-nodes were deployed. To optimize each L-node location, the Signal to Noise Ratio (SNR) was used. During this deployment, the LoRa SNR stayed in the range of –10 dB and +10 dB. A positive and significant SNR reading indicated a suitable location with sufficient signal strength. As every data packet sent via LoRa carries an SNR value as a complement with the actual data requested, the appropriate location of each L-node was straightforward to find and monitor. Due to the L-nodes being deployed with the expectation to operate for extended periods, uninterrupted reliability is a key element. Preliminary tests were run on the L-nodes once they were mounted on each asset to assess their ability to stay mounted and test and record their delay in transmission, SNR and signal reading. Once the initial testing was completed, each L-node was calibrated against the recorded values.

7.5 Results

The core idea from the work conducted was the development of a straightforward
technique that could help in the integration and installation of multiple heterogeneous units within an IIoT system.

The bottom-up flowchart shown in Fig. 13.35 illustrates the process to follow from asset identification through categorization of the asset to the module selection finishing at the endpoint of integration into an IIoT system. An example wind turbine is selected as the desired asset to be monitored, and the flow of the decisions is shown

**Figure 13.34:** Each pin marked L-(X) designates the installation location of an L-node and their corresponding number, while the location of the secure area is labelled separately [144].

**Figure 13.35:** A bottom-up flow chart visualization of the demonstrated technique [144].
in the bold text. The first stage is to categorize the wind turbine into a suitable class. From this classification, the sensors required, and the communications modalities are found. Typically wind turbines should be a passive infrastructure and thus require a low sampling rate. As wind turbines can be situated far from the control centre, often offshore or on mountainous terrain, the only usable form of communication would be LoRaWAN. Predominantly wind turbines towers are of a steel structure, and therefore a magnetic adhesion can be used. After all the low-level modules are chosen, the required layers can be extracted and then combined and installed as a complete and functional IIoT system.

For ease of data understanding and access, a dashboard-with-query application was created. Initially, a Dashboard application was developed, shown in Fig. 13.36, allowing for an efficient and concise view of the status of the L-nodes and the relevant sensors.

Using a radio-style button (shown in Fig. 13.36), the users can pick the corresponding desired asset, and a visualization of the previous hour of data recordings from each sensor of the selected L-node will be displayed.

Only using a dashboard can limit the volume of data that can be shown. The ability to see the historical data of an asset is critical. So, a second interface was created, where once the user inputs the relevant L-node ID, time and date, the desired information will be displayed.

Data is often shown graphically; however, other representations can also be applicable, as mentioned in previous sections. If a user is required to consult the database frequently, a mouse-oriented interface can be clumsy. To compensate for this clumsiness, a chatbot was added and configured to interpret questions aimed at the databases. The chatbot was built using RASA [149], an open-source machine learning framework to develop contextual chat assistants. An example question and answer from the chatbot is shown in Fig. 13.37.

Over the whole of the industrial demonstration, data was collected. To evaluate the capability of each unit used, data from each sensor on each L-node was analysed. As an example, vibration monitoring is an essential part of industrial asset monitoring. Figure 13.38 shows readings from the gyroscope (X, Y, Z) gathered during the operation of a diesel pump (Class-2 asset). Noise is often generated in industrial environments, and to compensate for it and smooth it, a moving average filter with a ten-second period was applied to the raw data.
7.4.1 Problems in IIoT Deployment

1. **Accessibility**: Industrial sites can be heavily restricted due to heavy machinery operating and other health and safety risk. During the installation of the L-Node, finding qualified personnel to provide aid was an issue.

2. **Line-of-sight**: LoRa wireless communication signal degrades when passing through dense infrastructure, which can be the typical setup in industrial areas. Thus, it is essential to find a secure site that is ideally visible to the location of interest to be monitored.

3. **Adhesion**: Different shapes, materials and biofouling can prove problematic for magnets or steel-straps to be used in conjunction with.

4. **Site Access Time**: All sites were active and carry out other activities from regular maintenance to new installations, and therefore the time allocated to test external 3rd party systems is restrictive even when deployed by external parties.
7.4.2 Solutions

To be able to adapt and overcome the challenges faced in the deployment of IIoT systems in an active site, a number of solutions were generated and given next:

1. **Accessibility**: Advanced planning and negotiation with the facilities staff can avoid unnecessary delays and issues.
2. **Line-of-sight**: Pre-mapping of the site and locating areas for optimal line-of-sight and locations where signal repeaters could be installed if required.
3. **Adhesion**: Where possible, pre-cleaning any biofouling would aid in the adhesion or the application of drilling or welding for a more permanent method.
4. **Network Connectivity**: Deploying a secure network separate from the facilities owner’s network ensures a connection and reassures the owners there is no data at risk.
5. **Site Access Time**: As with accessibility, advanced planning and negotiation can reduce this risk.

Applying all the previous solutions and the bottom-up systems approach shown in Fig. 13.35 to the process of designing an industrial deployment of one or more CPS allows for the following:

- Problems to be spotted and neutralized before they occur (poor line of sight – repeaters required)
- Optimize the in-situ data (recording frequency and length, visualization, and query method)
- Planned avoidance of human interaction to minimize viral transmission risk.

8. Connect-R

Decommissioning structures, for example, gas platforms or nuclear storage tanks, is challenging and the cost of the dismantling, as well as the effect and impact of the surrounding environment, are among some of the factors that must be included and anticipated on an asset management system as these can be extremely costly and environmental conservation standards must be met.

There is pressure for oil, nuclear and gas, and similar industries to increase their profitability whilst growing the business. Here, the correct IAM strategy will maintain and service their equipment in a time-effective manner whilst increasing equipment lifetime and maintaining low costs as it is essential that they keep their critical assets working efficiently whilst being effectively serviced.

These types of industries are filled with heavy-duty assets and they can often be sizable or located at great distances from the other, hence remote and accurate real-time data is essential in these circumstances for effective and adequate asset management.

As mentioned previously, technological advances, through the digital transition, have enhanced maintenance operations. Some of these technologies include 3D scanning, mapping, and predictive maintenance, which allow for much-improved monitoring and maintaining industrial assets.

In these industries, in particular, the working environments can often be hostile and extreme. Such situations and environments create challenges in maintaining monitoring assets as they can often pose health risks to personnel and therefore should not be performed by personnel. This is particularly true in the nuclear industry due to
the risk of personnel being exposed to high radiation levels as well as unstructured environments. Operating in an extreme environment can have an effect on asset management structures and management strategies due to risk to human life and the increasing cost of operations. However, this can be mitigated through the use of robots and in-situ sensor technology.

Connect-R is an industrial sized self-building modular robotic solution that provides access to hazardous environments on industrial work sites through a multi-robot system (MRS). The system is a resilient and robust autonomous robotic system. This modular robot is a structural robot that can form into a variety of, required, physical structures to allow access to an extreme environment without the requirement of a human. The structure that is formed by the modular robots creates a path for other robots to traverse regardless of the unstructured environment surrounding it. Once in the environment, these smaller robots are able to perform a number of tasks such as repair and diagnostics to provide real-time data and mapping through the use of various, suitable sensors and end effectors [150].

9. Future Challenges

While some future challenges can be predicted, such as dealing with an increasingly large number of ageing and failing industrial assets coming to the end of their predicted life, others such as the COVID-19 pandemic could not have been foreseen. However, it can be observed throughout this chapter that the greatest challenge is still to keep humans safe, whether that is from a virus, storms or radiation. To keep them safe the continued deployment of CPS is essential, but it must go further, as at present humans are still required to deploy the robots and to retrieve them. Two different methods can be used to separate humans further from danger, (1) Resident Robots and (2) Fluidic Logic Systems.

9.1  Resident Robots

Instead of a robot being stored and then deployed manually by a human, resident robots are already situated “in residence” close to or on the asset itself. A simulation can be seen in Fig. 13.39. These robots can be autonomous but also can be operated from the shoreline remotely. Minimal human interaction either with the asset or robot is required unless remedial action cannot be completed by a robot. Resident robots would also provide enhanced operational overview due to DTs, therefore an allowing for a greater understanding of what status is and what is going on with an asset. Within these expansive DT asset management methodologies are built-in as well as robot fleet integration.

9.2  Fluidic Logic Robots

An issue when deploying RAS in areas of radiation can be the degradation or failure in the performance of the on-board electrical control systems and thus the entire robot itself. While sensitive systems can be shielded and often are, they will still degrade and will also become contaminated and un-retrievable. One approach to dealing with this degradation issue is by removing the electronics in their entirety. As mentioned previously, there are groups working in the area of fluidic logic where typical electrical systems are replaced with a functional fluidic analogue. If the fluid
and structural material were non-ionizing in nature, this would alleviate one aspect of the degradation problem [153].

10. Conclusion

It can be seen from the trends that the incorporation of RAS and CPS into industrial asset management was progressing. However, the COVID-19 pandemic has driven this deployment to rapidly advance the approach for CPS (due to the requirement to work remotely) in achieving the roadmap to trusted and safe autonomy within robotics and asset management methodologies.

At the start of the chapter, a question was posed “How can the new dangers of a pandemic and the past dangers of the extreme environments can be mitigated using cyber-physical systems?” A theoretical SSOSA and multiple pilot studies were given as examples of ways in which these dangers can be reduced if not mitigated fully.

The SSOSA acts as the theoretical model, which ensures the mutualistic approach enhancing the interaction across human, infrastructure, robot and the environment. The SDA represents system engineering to enable the interaction via bidirectional communications with knowledge sharing across the system elements, which are required to be integrated for advanced CPS. This can encompass asset management methodologies, O&M, deployment and fleet management which can be seen in an operational overview within a DT.

The bottom-up systems approach provided a foundation for how to assess potential issues and pit falls on industrial sites, which can be easily modified to
incorporate COVID-19 specific restrictions allowing for straight forward deployment of CPS with minimal risk to the operators.

Both of these implementations featured CPS be they robots or sensors being used for scanning and monitoring of infrastructure, while the third implementation discusses the work being done on how to use MRS in areas where humans cannot tread, and standard robots require help to allow for an adaptable robotic structure to be custom fabricated made of itself for other robotic systems to traverse.

The system engineering discussed display how both current and future work environments can be created with the idea in mind of minimal to no human intervention being required. This reduces the risk of accident or injury coming from dangerous environments or viral transmission from COVID-19, or future pandemics.

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