Verifying Autonomy for Offshore Renewable Energy Applications

ORCA HUB
Offshore Robotics for Certification of Assets

CATAPULT
Offshore Renewable Energy

UNIVERSITY OF LIVERPOOL

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Royal IHC

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Contents

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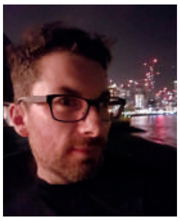

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Guest Foreword: Simon Reeve

Offshore renewable energy is now a major contributor to the energy supply portfolio in the UK and increasingly around the world. In 20 years, the offshore wind sector has grown from a standing start to providing a critical share of electricity generation. Adding to this wind portfolio is the growing application of marine energy systems, either as stand-alone tidal devices, or integrated with other technologies as part of offshore energy production platforms.

Significant experience in building, operating and maintaining this fleet has been gained and knowledge of decommissioning is now being added to the skill set. However, most of these operations still rely on high levels of human physical access, working in challenging and hazardous environments.

The past 5 years has seen a rapid rise in the development of digital technology solutions in all sectors, reducing the need for human intervention, providing remote operation, inspection and maintenance services. Technology developers seek opportunities to pilot, demonstrate and validate the performance of their robotic solutions against exacting technical and safety specifications. Wind farm owners and operators seek assurance that a remotely operated service can provide them with at least the same degree of confidence as they get from human verification.

This technology development and validation path is not new, it is well established across many sectors. So what are the specific challenges in the offshore energy sector?

The sector is thinking afresh about the challenges it is trying to address. For example, is it simply trying to automate a human process in order to operate machines that were designed from the outset for human intervention and control? Or is it seeking to design for autonomous operation from cradle to grave?

This latter approach moves away from considering robots as replacements for humans and forces us to think at a system level in terms of what increasing autonomous control really means. It also jumps the initial efficiency loss usually experienced when moving from human to remote control and enables increased safety and efficiency to be realised together in the autonomous system.

A further challenge for the offshore energy community and the stakeholders it serves, is whether it can replicate the recent impressive growth in scale of installation with a similar rate of change in remote operation and autonomous working. Will adoption and deployment of robotics technology alone be sufficient to meet this target, or will it also need to harness other new skills and new ways of thinking?

This report is a timely collation of the current status of new technology and thinking available to support the offshore renewable energy industry. In particular it explains the importance of robust verification and validation processes in meeting the challenges above. Successfully bringing these two elements together are vital if the industry is to serve as a benchmark for the safe application of robotic and autonomous systems in hazardous environments for the next 20 years.

Simon Reeve

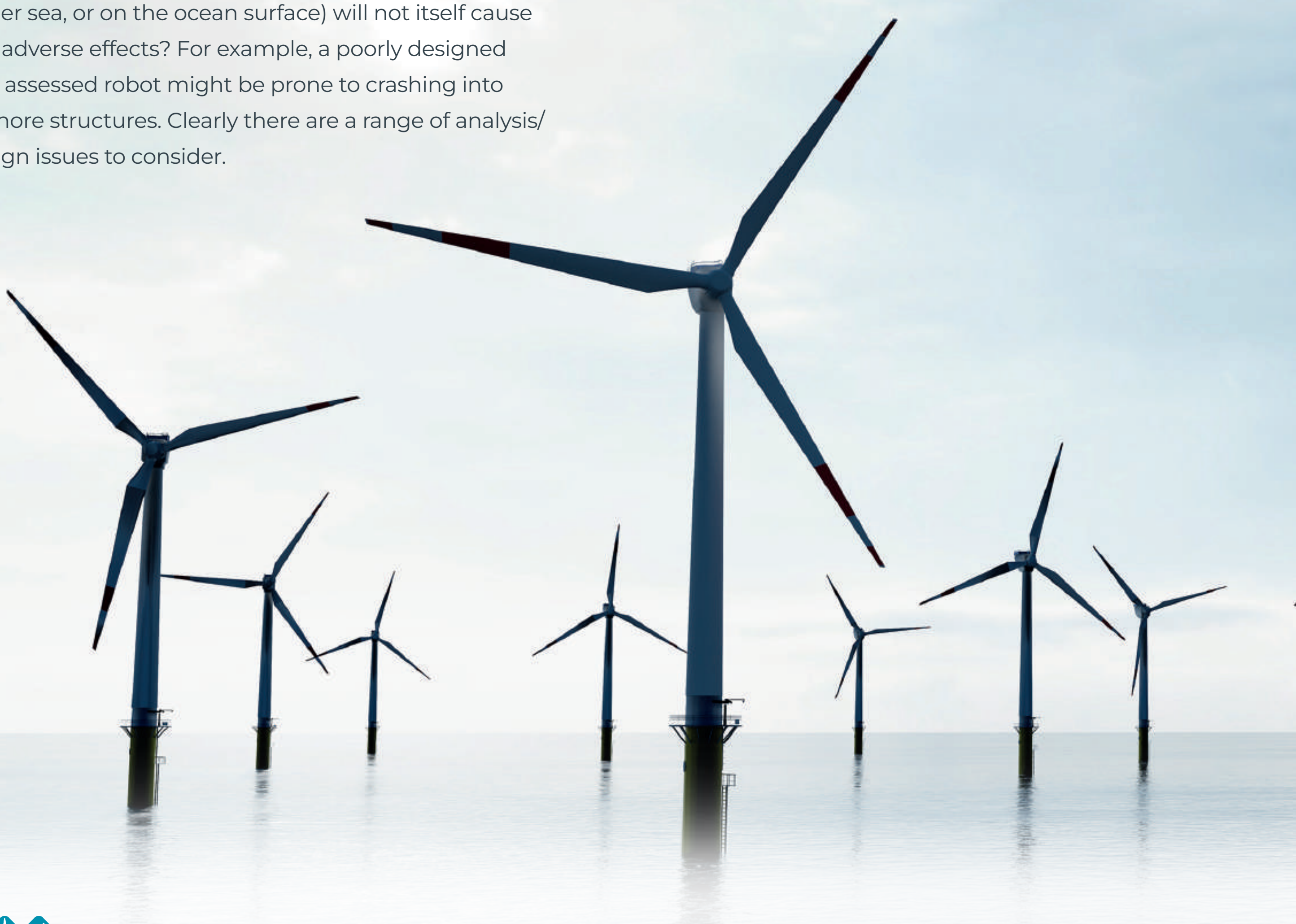
VP Technology & Innovation, Lloyd's Register Group

Chair ORCA Hub Independent Steering Committee

I. Introduction

Security in the generation of energy is essential to economic progress [1]. Decreasing fossil fuel supplies and increasing environmental concerns make renewable energy generation vitally important [2]. As a result, offshore renewable energy is a rapidly growing industry. Denmark introduced the world's first offshore wind farm in the early 1990s and since then the sector's development has continued to accelerate. Globally, more than 35.7 Giga-Watts (GW) of offshore wind power is currently installed, comprising of just over 8,000 individual turbines. A further 38.3 Giga-Watts (GW) of offshore wind power is under construction [3]. Sending human engineers to carry out offshore inspection and repair activities can be both dangerous and expensive, and so the idea of using Robotics and Autonomous Systems (RAS) to handle such tasks is appealing. The use of such systems is likely to improve safety aspects since personnel are removed from the dangerous environment. Furthermore, cost reductions and increased energy yields through better optimised operations and maintenance are possible. However, can we be certain that the robotic system (be it in the air, under sea, or on the ocean surface) will not itself cause any adverse effects? For example, a poorly designed and assessed robot might be prone to crashing into offshore structures. Clearly there are a range of analysis/design issues to consider.

Once we have a situation where a robotic system is successfully carrying out offshore activities, controlled from a remote (and onshore) human operator, then the next desirable step is to move towards autonomous behaviour. The key aspect of autonomy is that decisions, and often actions, will now be undertaken by non-human actors. So, rather than being directly controlled by the onshore operator, an Autonomous System will itself make at least some of the decisions, and take some of the actions, that used to be the responsibility of the human operator. Delegating responsibilities for decisions to machines, often software, in this way has strong implications about the levels of confidence required concerning the software and its mechanisms for making decisions. How much of the human responsibility is delegated to the system will lead us to a range of autonomy levels (which we will outline later). As we move towards allowing the Autonomous System to take responsibility for very significant activities, then we will require much stronger and more definite verification techniques.



Although the move to use autonomy appears to be a very complex step-change in technology, there are very significant gains in efficiency and effectiveness that can be achieved. Remote control of robots, especially in very dynamic environments, is often error prone. Furthermore, the speed of reaction is limited by the human operator and communication systems lag/reliability. Moving to autonomous robots may not only reduce the burden on the operator, thus allowing them to monitor multiple autonomous vehicles, but can potentially lead to much more efficient and effective inspection and repair. However, the move to develop autonomy requires new forms of analysis and design to ensure that this is safe and reliable [4].

This paper aims to provide researchers, developers, and regulators with an overview of the tools, techniques, and issues that may be relevant to offshore renewables. We are considering a range of offshore robots, such as autonomous surface vessels, and will highlight the role of verification and validation techniques for assessing these new, often autonomous, behaviours. It is important to note that we do not aim to cover aspects that are already assessed as part of non-autonomous and non-robotic systems. For example, we will not consider aspects such as materials, propulsion, structure, etc. However, we will be considering the new issues brought by robotics and autonomous systems wherein most of the novel behaviours are provided by (new) software.

There will undoubtedly be new developments, beyond those described here, in the ever-changing world of AI and autonomy for offshore renewable energy applications. As such we see this article as a first step in capturing key issues in this area and a potential source of discussion for stakeholders in the sector.

The structure of this paper is as follows. In Section 2 we provide background information on the offshore renewable energy sector and the current role of autonomous systems. In Section 3 we describe some of the verification and validation practices currently being used to assure the safety and reliability of the autonomous systems. Following this, in Section 4 we explore how autonomous systems can be designed with verification and validation in mind. Subsequently, in Section 5 a case study is provided in which some of the practices and approaches from the previous two sections were used to verify and validate an autonomous surface vessel at Royal IHC. Finally, in Section 6 we provide conclusions concerning the present and future use of autonomous systems in offshore renewable energy and the importance of verification and validation.

2. Background

In this section we provide background information on the existing and potential use of Robotics and Autonomous Systems (RAS) within the offshore renewable energy sector. We focus primarily on offshore wind rather than marine energy since marine energy is a nascent industry and operations and maintenance practices remain relatively undefined. In contrast, offshore wind technologies are more well-developed [5]. It is important to note, however, that marine energy could also see significant health, safety, and cost improvements by adopting truly autonomous systems, despite being at a very early stage of development. Tidal developments, for instance, are located in high-current environments making diver-led inspection and repair operations both hazardous and time sensitive.

A. Offshore Wind

Offshore wind farms are difficult to access. Some are located close to shore (<5 km), whilst others can be over 100 km from shore, e.g., the Hornsea One[1] wind farm. This makes accessing the site throughout the wind farm's lifecycle both challenging and expensive, particularly for operations and maintenance activities. Charter rates are expensive for manned marine vessels. This adds a significant cost driver for the adoption of Robotics and Autonomous Systems (RAS). Near-shore sites are typically serviced by small crew transfer vessels (up to 24 crew). Further afield sites are increasingly adopting other models, utilising large Service Operation Vessels, some with "walk to work" (gangway transfer) capability. These large vessels are often accessed by helicopter [6].

In the United Kingdom, and indeed Europe, much of the installed offshore wind capacity is in the North Sea. Water depths range from very shallow sites at less than 10 m to more than 50 m for foundations that are grounded on, or in, the seabed. Floating foundations are becoming an option for deeper waters, and these are likely to become more prevalent in the coming years [7].

Sea state is critical to the accessibility of wind turbines, especially for those serviced by small crew transfer vessels. Accessing assets can be a hazardous undertaking for wind farm technicians, informed by strict weather-condition boundaries. Reducing the need for manned interventions on turbines presents a health and safety driver for the adoption of RAS.

Many operational and maintenance tasks (discussed in more detail below) involve either working in hazardous environments or working far from shore. There is therefore a vested interest, both in terms of health and safety and cost reduction, to increase the usage of RAS in offshore wind. Autonomous systems in particular can potentially move humans away from the hazardous offshore environment while increasing efficiency, therefore offering the greatest potential for cost and risk improvements. There is also the motivation to exploit RAS technologies to reduce the downtime of wind turbines and increase overall energy production.

"Charter rates are expensive for manned marine vessels. This adds a significant cost driver for the adoption of Robotics and Autonomous Systems (RAS)."

[1]https://hornseaprojectone.co.uk/

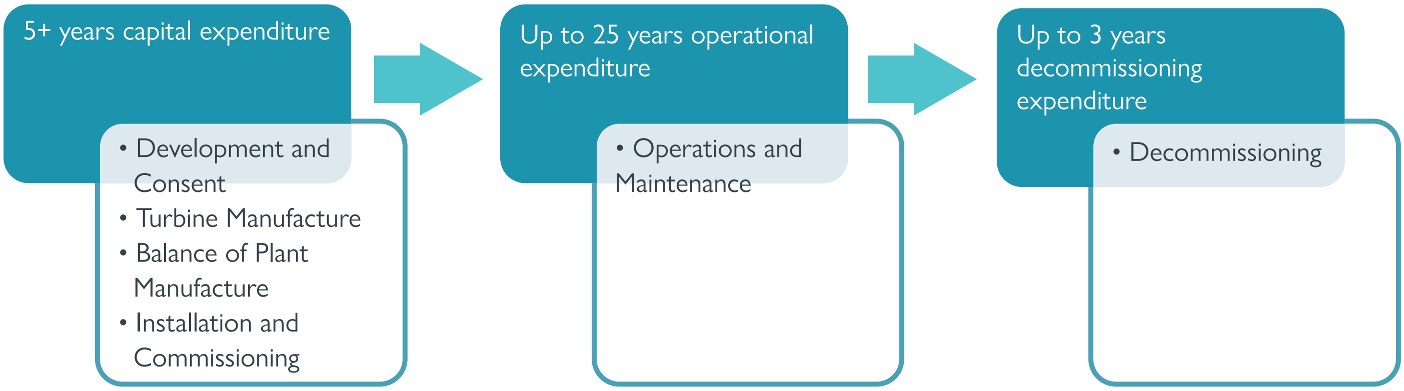


Figure 1. Offshore Wind Farm Lifecycle

1. Envelope of operations

An offshore wind farm development has a lifecycle of more than 30 years from planning to decommissioning (see Figure 1) [8]. RAS has various roles to play in almost all these stages of a wind farm's development, from planning and consent to installation and commissioning, operations and maintenance and decommissioning.

During planning and consent, a large amount of data collection is required to inform the environmental impact assessment, satisfy consenting bodies, and define the site layout and optimisation. Datasets required are mostly environmental, e.g., resource assessments, seabed surveys, sub-bottom profiling, and assessments of current and sediment flows through the site. Non-environmental surveys, for example surveys concerning unexploded ordinance, are also required.

Installation and commissioning require close monitoring to ensure safe and effective implementation, a task well suited to unmanned aerial systems. For cable and foundation installation, Remotely Operated Vehicles (ROVs) are commonly used; robotic systems with increased autonomy could conceivably replace these in the medium term.

Most use-cases for RAS are in the operational phase of an offshore wind farm. Components that require regular inspection include blades, foundations, and buried cabling (potentially using unmanned aerial systems and unmanned underwater vehicles). Internal inspections are required on a regular basis to satisfy statutory and warranty requirements. It is expected in the coming years that unmanned systems may begin to take on repair and maintenance tasks on the turbine as well as inspection.

Consenting conditions require regular surveys of the wider site (e.g., sediment scour and movement) to ensure minimal environmental impact of the wind farm [9].

Decommissioning will likely involve removing the whole turbine and foundation to below the mudline. Very few offshore wind farms have been decommissioned to date, and those that have are small in scale. As a result, it is difficult to assess accurately the role that RAS may play. However, just as RAS is expected to play a central role in, for example, nuclear decommissioning we would expect RAS to be just as important in decommissioning offshore renewable sites.

As described here, unmanned systems are already contributing to wind farm operations to a greater or lesser degree in most, if not all, stages of a wind farm development. As technology develops, these systems will become increasingly automated, and eventually autonomous (see Section 2-A3). It is therefore essential for customers and end-users to have these autonomous technologies as de-risked as is reasonably practical. The system must be verified and validated properly, with testing and demonstration being vital in increasing confidence. This will ensure not only that the system can carry out its intended task, but that it does it as expected, within the requirement boundaries that have been set, and without posing a risk even if the system strays outside of its programmed envelope.

Figure 2. Sheringham Shoal Offshore Wind Farm (Source: NHD-INFO, Flickr)

2. Offshore Wind Assets

This section provides a brief overview of the different kinds of assets within offshore wind renewable energy. For more information on this subject please see [8].

Wind farms vary greatly in area, depth, and distance from shore. Small farms and demonstrator sites may take up as little as 5–10 km^2, whilst the largest offshore wind farms exceed 600 km^2 in area, greatly increasing the potential savings that could be harnessed with the use of RAS. Likewise, sites that are further from shore can benefit more. Early developments were often less than 10 km, whilst the largest new developments can now be over 100 km from shore. Fixed bottom wind farms (i.e. foundations that are fixed to the seabed) are found in water depths up to 60 m. Floating wind farms, which utilise buoyant foundations that have been moored to the seabed, can use water depths much deeper than this.

Wind turbines (as shown in Figure 2) consist of several major components. The external components will be the focus here, since these have the greatest potential to be inspected, maintained, and repaired in the short to medium term. Offshore wind turbines utilise several types of *foundation*, typically fixed to the seabed. The two most common types are monopiles (rolled steel driven into the seabed) and jackets (steel lattice structures fixed to the seabed). Floating foundations, which are increasing in use as the technology develops, also come in several forms, from large spar buoys and floating barges to tensioned platforms [8].

On top of the foundation, a *transition piece* joins the turbine itself to the foundation. The transition piece allows access to the turbine and has a gantry. The *tower* consists of rolled steel sections joined by bolted flanges and welds. For the largest turbines that are now beginning to be manufactured, these can be up to 150 m in height, and is expected to increase as turbine power increases.

Figure 3. Offshore Substation (Source: Ramboll)

Finally, the *nacelle*, which houses the power train, is mounted on top of the tower. At the front of the nacelle, is the hub, onto which the blades are fastened. Offshore wind turbine blades have carefully designed aerodynamic shapes to capture the maximum possible amount of energy from the wind, and so require careful maintenance. The largest blades are now over 100 m long.

Subsea Cables associated with an offshore wind farm have two main types. The first is the *inter-array cable* which connects wind turbines in "strings" of several turbines. These deliver power from the turbines to the offshore substation. The second is the *export cable* which is used to take power ashore from an offshore substation. Export cables therefore require a much higher power rating than inter-array cables. Both types of cables are typically buried. However, these can become exposed due to sediment movement or disturbance from other parties, e.g., trawlers, resulting in cable faults. Such faults are one of the most common causes of power loss from a wind farm.

Offshore Substations (see Figure 3) receive power from the turbines on a wind farm. Here, the voltage is stepped up to a much higher level. This reduces power losses incurred exporting the power to shore. Depending on the size of the wind farm there may be one or two substations.

"Wind farms vary greatly in area, depth, and distance from shore. Small farms and demonstrator sites may take up as little as 5–10 km^2, whilst the largest offshore wind farms exceed 600 km^2 in area, greatly increasing the potential savings that could be harnessed with the use of RAS."

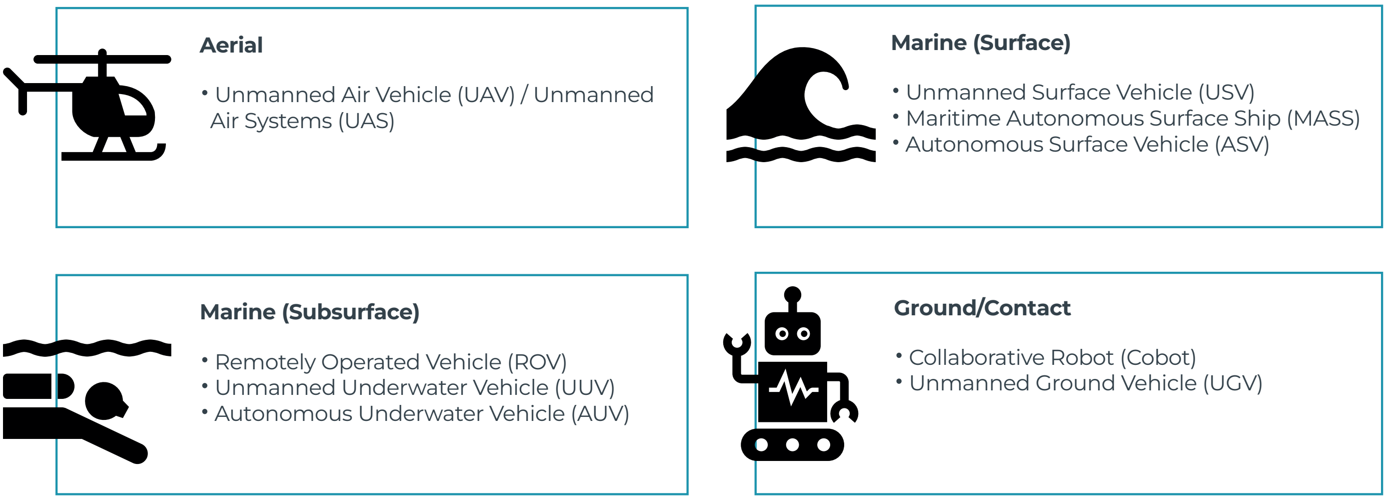


Figure 4: Domains of Robotic Systems.

3. Autonomous Systems in Offshore Wind

RAS vehicle platforms can be classified in a variety of different ways depending on the domain of their application. These typically take the form of the categories described in Figure 4. These distinct robotic vehicles can perform a range of different tasks that are specific to these domains, but they can also be broadly divided into “sensing” and “manipulation” capabilities. Sensing involves inspection of a component or wind farm asset, which can be performed remotely or through Non-Destructive Testing (NDT) contact. Manipulation involves direct interaction with a wind farm component to perform maintenance or repair duties.

The incentive behind utilising RAS technologies in offshore wind is to mitigate the influence that the harsh environment imposes on activities throughout the lifecycle of an offshore wind farm, which primarily affects both cost and safety risk. RAS can help alleviate these areas of concern through the reduction of maritime logistics, labour requirement onsite, and wind turbine (and other assets) downtime. Presently, the use of robotics in offshore wind involves a considerable amount of human interaction, for deployment/ retrieval, piloting, and supervision. However, if the full benefits of employing RAS technologies are to be realised, resident or remotely deployable systems that require higher degrees of autonomy would have to be exploited [10].

Whilst the size and number of offshore wind assets installed makes RAS attractive to site owners, there are other factors that further increase the utility of these systems in offshore wind farms. For example, whereas there are several offshore wind turbine manufacturers, all turbines take roughly the same form making robotic technologies easily transferable across the industry. Furthermore, all the turbines across a wind farm are virtually identical. Turbines are widely spread out, however, making them expensive and time-consuming to monitor with manned visits. Finally, the conditions experienced offshore means there is a significant health and safety driver to reduce manned operations. High winds and waves, strong currents and precipitation, poor visibility and the increased degradation of structures and systems caused by weather, seawater, etc. All these further increase the appeal of RAS.

We now examine the applications of RAS with respect to the domains shown in Figures 4 and 5. Aerial robotics in offshore wind typically takes the form of commercial remote-controlled drones that are utilised for external inspection of wind turbine blades and wind farm substations, with one technician required to remotely pilot the drone and another to control the camera, usually. For example, Cyberhawk uses remotely controlled unmanned aircraft to conduct close visual inspections of offshore wind turbines for clients such as offshore wind turbine manufacturer

Figure 5. Surface, subsea, ground and aerial robots for offshore environments. (Source: ORCA Hub.)

Siemens Gamesa [11]. Piloted inspections such as these can be conducted from a Crew Transfer Vessel (CTV) but would ideally be conducted from a fixed platform where motion is stabilised. Several drone service providers are now able to automate aspects of these inspections as a commercial offering.

Unmanned Surface Vessels (USV) often replace larger footprint, manned surface vessels used for hydrographic surveys of the seabed. Information on other wind farm assets can also be extracted, such as wind turbine/electrical substation foundations and array/export cables. For example, ASV Global has developed a range of Autonomous Surface Vessels (ASVs) which are used for surveying and ocean data collection such as the C-Worker 7 [12]. Section 5 contains a detailed case study of an ASV application for an offshore wind farm.

Subsea operations are currently performed by tethered ROVs. These are carried out from a suitable vessel that can deploy and recover the vehicle. Communication and control of the ROV is enabled by an umbilical or tether cable, as well as the electrical power to carry out operations. The umbilical is strengthened to deal with the mechanical loads inflicted by the sea. ROVs are typically utilised for inspection of underwater assets, such as foundations or cable routings, and can be equipped with a wide range of tools and manipulators to carry out specific tasks, such as cable trenching for installation [7]. AUVs such as the iRobot Seaglider used by the University of Washington have also been used for oceanographic surveys for almost 20 years [13]. The use of USVs as a "mothership" to deploy daughter vehicles (ROVs or AUVs) is also being explored as a remote survey, inspection and maintenance capability.

The range of vehicles in the ground/contact domain incorporates a range of locomotive conveyance and are still at a relatively early level of adoption in offshore wind. Walking/wheeled/treaded robots can be utilised for operations involving a fixed platform onshore, on a wind farm asset or the seabed floor. For example, the ANYbotics ANYmal walking robot was used for a trial offshore inspection task in 2018 [14]. Magnetised vehicles are able to traverse the ferrous tower and foundation structures, whereas vehicles can exploit other adhesion technology, i.e., vacuum adhesion, for manoeuvring on a non-ferrous surface, such as a wind turbine blade.

B. Levels Of Autonomy

Unmanned systems can operate with different levels of autonomy depending on their requirements. The Pilot Authority and Control of Tasks (PACT) taxonomy, developed by the UK Defence Evaluation Research Agency [15], and revised at BAE Systems (UK) [16], provides a useful and influential description of how the levels of autonomy within an autonomous system can vary (see Table 1).

The highest level of autonomy, 5b, involves all key activities/decisions being carried out by the system, potentially without human involvement, while at level 5a the system chooses and performs actions and informs the operator of what it has chosen to do. Most "fully autonomous" systems will naturally exist at a level between levels 5a and 5b, in which the autonomous system keeps the operator informed but does not overload them with unnecessary information.

Level 4 relies on human supervision: a 4b system selects an action and performs it unless the operator disapproves; a 4a system selects an action and performs it only if the operator approves. At level 3, the autonomous system suggests options to the operator, and can propose and perform one of them if directed by the operator while, at level 2, the autonomous system only offers advice to the operator in the form of optional actions that could be taken, much at the level of a "decision support system". At level 1, this advice is only given if requested by the operator and, at level 0, the operator fully controls the system.

One important aspect of PACT levels of autonomy is that a system's level need not remain fixed and can be adjusted during operation. For example, an operator may wish to allow an autonomous system to pilot itself to the site of an offshore inspection asset, taking over control once the system has reached the site. Therefore, the operator might set the PACT level of autonomy at 5a for the first portion of the mission, and then reduce it to 3 or below when the system has reached the target location. This variable autonomy is a common feature of more sophisticated and autonomous application scenarios. Clarity over autonomy levels (and operator expectations) at different stages of a mission is crucial.

PACT Level of Autonomy	Description
5b	System does everything autonomously
5a	System chooses action, performs it and informs operator
4b	System chooses action and performs it unless operator disapproves
4a	System chooses action and performs it only if operator approves
3	System suggests options to operator and proposes one of them
2	System suggests options to operator
1	Operator asks system to suggest options
0	Operator controls system

Table 1: PACT levels of autonomy [15]

Figure 6. Offshore technician. (Source: iStock)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3. Verification and Validation Practices

A central concern within the development of autonomous systems for deployment in hazardous environments is ensuring the reliability and robustness of the proposed systems. Reliability is especially important wherever autonomous systems are placed in mission-critical scenarios where loss of life and damage to property and infrastructure pose severe risks. In addition, hazardous environments are highly uncertain and unpredictable, and therefore autonomous systems designed for such environments must be robust and reliable so that they can maintain safety and reliability throughout their operation.

A common safeguard on the development and deployment of new technology is Verification and Validation (V&V) [17]. In this process the progression of a technology is directed by a set of formally identified customer requirements, which is then used to inform a functional specification. This specification continues to be defined with increasing granularity, progressing through development, and eventually culminating in acceptance testing against the original user requirements. A traditional view of this process is given in Figure 7.

The iterative process of V&V within this methodology is crucial for the development of new technology. Intermediate cycles within the process ensure that at various stages the technology is checked against original design specifications and customer requirements. The process supports the development of solutions which are fit for their intended purpose. Although hierarchically related, customer requirements and design specifications often have different objectives and therefore different measures of success. If a design specification is an accurate description of the system requirements, then much can be done through verification, though there it is likely that there will be some requirements that cannot be formalised in this way. Two common aims of V&V are to establish that (i) the system performs as desired, and that (ii) the system does not do anything undesirable. The latter point is easily overlooked, and often more difficult to show than the former, but it is vital for V&V engineers to consider unintended uses and side effects of a system.

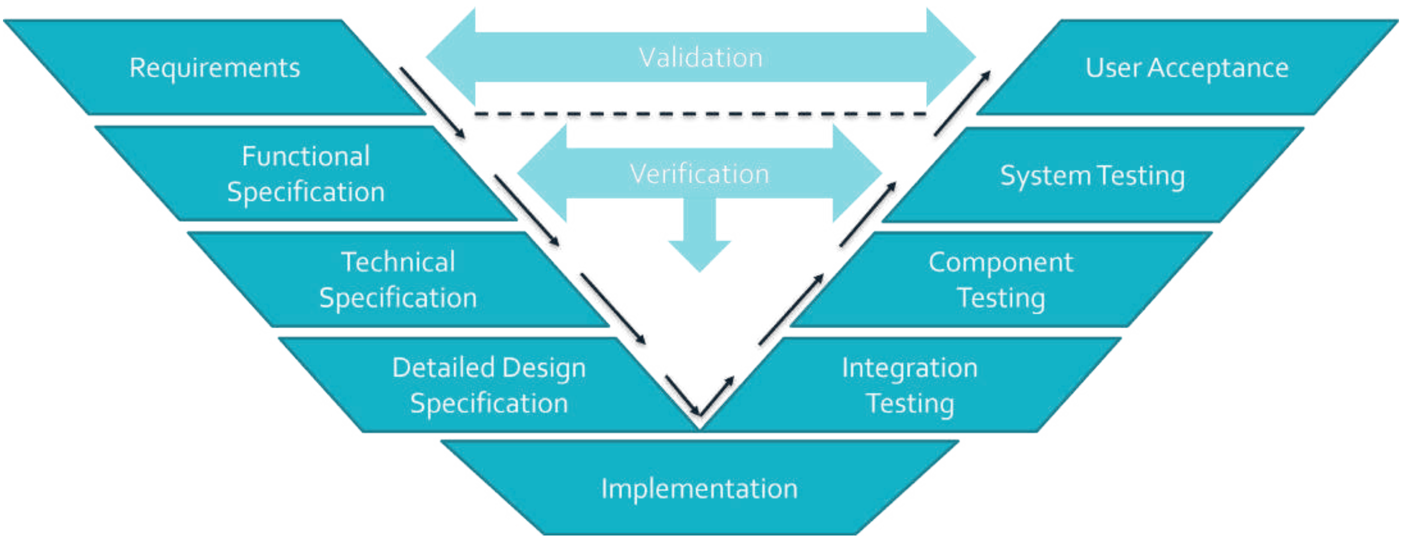


Figure 7. Verification & Validation process.

According to ISO Standard 8373:2012, on *Robotics and Robotic Devices* [18], the distinction between verification and validation is defined as:

Verification - *"evidence that the requirements have been fulfilled," i.e. are we building the system correctly?*

Validation - *"evidence that the requirements have been fulfilled,"* i.e. are we building the correct system?

A key issue in V&V is model–reality mismatch. V&V techniques often rely on the use of models of (i) the system under analysis, and/or, (ii) the target environment for the system. For example, an unmanned aircraft might be tested within a wind tunnel to verify its stability in flight. However, the wind tunnel is only partially realistic and is far more predictable than a real-world operating environment. Another example of the use of models is in high–fidelity simulation (discussed later in Section 4-D) where both the system and the environment are modelled. To use the unmanned aircraft example, a model of the aircraft can be tested in a model of the target environment during simulation. In this case, the model–reality mismatch is twofold due to inaccuracies in both the system model and the environment model. For this reason, it may be favourable to use a variety of V&V techniques and performance metrics to ensure that the model–reality mismatch is minimised through the use of independently-generated models.

A variety of V&V techniques can be used for RAS, including physical experiments and testing, simulation-based testing, automated software testing, hardware-in-loop testing [19], formal methods [20], and more. Each V&V technique has its strengths and weaknesses, meaning that a thorough V&V strategy should involve several complementary techniques. Ideally, V&V should be integrated throughout the system's development life cycle. For example, a design can be validated with respect to requirements, and prototypes (discussed further in Section 3-A7) can be verified and validated throughout implementation, operation, and maintenance phases.

Within the RAS field, the range of V&V options can become large and bewildering. At one extreme, formal methods provide very strong guarantees of behaviour, but are infeasible for large/complex systems [20]; at the other extreme, practical testing is an important element but provides only weak guarantees of future behaviour. In most scenarios, a combination of techniques will be required [21], [22].

In the following subsections we describe the different verification and validation techniques available for RAS. Note that this list is provided for illustrative and informative purposes and is not intended to be exhaustive.

A. Physical Testing And Test Facilities

Physical testing is a well-known V&V technique. In physical testing, the system (or subsystems, components, or materials of the system) is operated within controlled, realistic, experimental scenarios which are monitored to determine the effectiveness of the system with respect to its requirements and design. As physical testing can be hazardous it may be necessary to perform tests in a restricted or isolated environment, or an environment with additional safety and security controls and constraints. For example, for an autonomous surface vessel, it is possible that a faulty autonomous control system may cause the surface vessel to collide with other vessels, and therefore physical testing in this case must be conducted in a restricted environment. In general, physical testing is expensive, time-consuming, and labour-intensive, as tests can be wide-ranging in space and time, and errors within the system may cause damage to the system or the test environment. In addition, both replication and coverage can be problematic, if not impossible. However, the realism and challenge of physical testing make it a vital part of any V&V strategy. It is also very tangible to potential nontechnical customers and end-users, making it a valuable part of 'selling' innovative systems. We must not underestimate the "confidence" given (even when not fully justified) from seeing a robot or vehicle acting in a realistic environment.

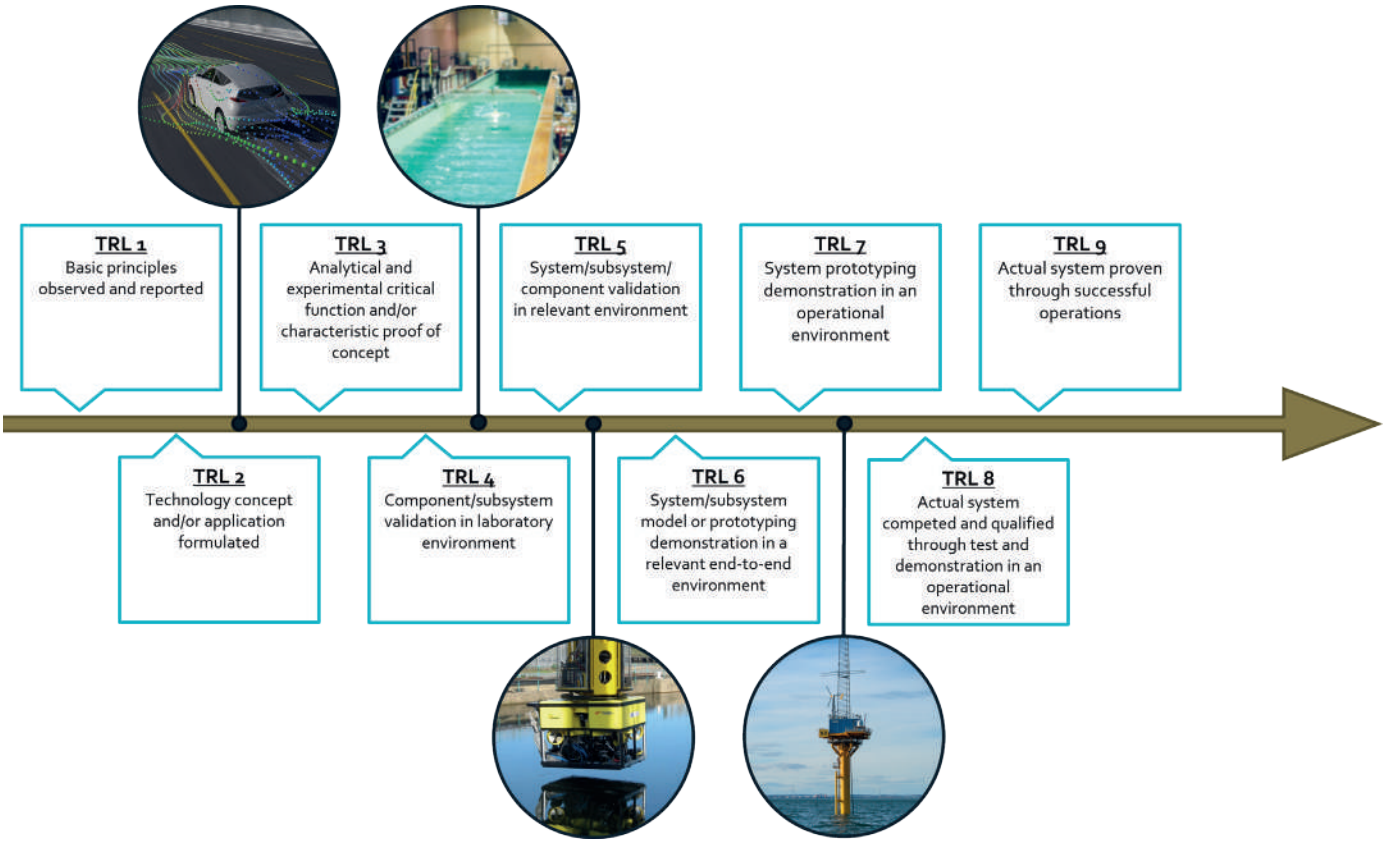


Figure 8. Test facilities are required at all levels of the TRL scale (the scale used here was developed by ARENA) [16].

Development of any technology is fraught with challenges. It is highly unlikely that a technology can move from a lab-scale model/CAD concept to a commercial project in one step. It is essential for technologies to be de-risked for multiple reasons:

- It is expensive to develop a commercial technology, and not every technology can be successful.
- It is undesirable to develop a technology at a scale suitable for commercial applications only to discover it is flawed/unsuitable.
- Technology development, especially by small/ medium sized enterprises (SMEs), is often dependent on grant funding. As the Technology Readiness Level (TRL — see Figure 8) increases, the suitable grant funding mechanisms expect more from technology developers in terms of previous development activities and evidence of performance/feasibility.
- Start-ups and SMEs often look to seed funds, angel investors or similar, to support funding of activities. One element that would be investors need to have confidence in (although by no means the only element) is the feasibility of and demand for a technology. The ability to test and demonstrate at multiple scales with clear outcomes is therefore imperative. We now examine the different types of physical testing.

Figure 9. AUV tank testing at Heriot-Watt University's Ocean Systems Lab. (Source: Heriot-Watt University)

1. Laboratory Testing

In order to test basic autonomous functionality, a low-risk easily accessible environment is required (such as that shown in Figure 9). At this stage there may be a large amount of software troubleshooting required that has not been apparent in simulated tests. It is therefore important that many iterative tests can be run in a short space of time, with little or no set up required. Laboratory scale tests, such as open warehouses or indoor test tanks provide easily accessible areas to do such testing. However, operational environments present significant challenges that are difficult to replicate— this is a significant drawback of laboratory testing.

2. Representative Testing

Representative test facilities add an additional layer of realism to testing activities. This is usually in the form of environmental conditions that an autonomous system may have to respond to in the field. For instance, a wave tank may be used to test how an autonomous system avoids obstacles in the presence of unpredictable currents, or an ex-service blade from a wind turbine could be used to test the control system of a robot (as shown in Figure 10).

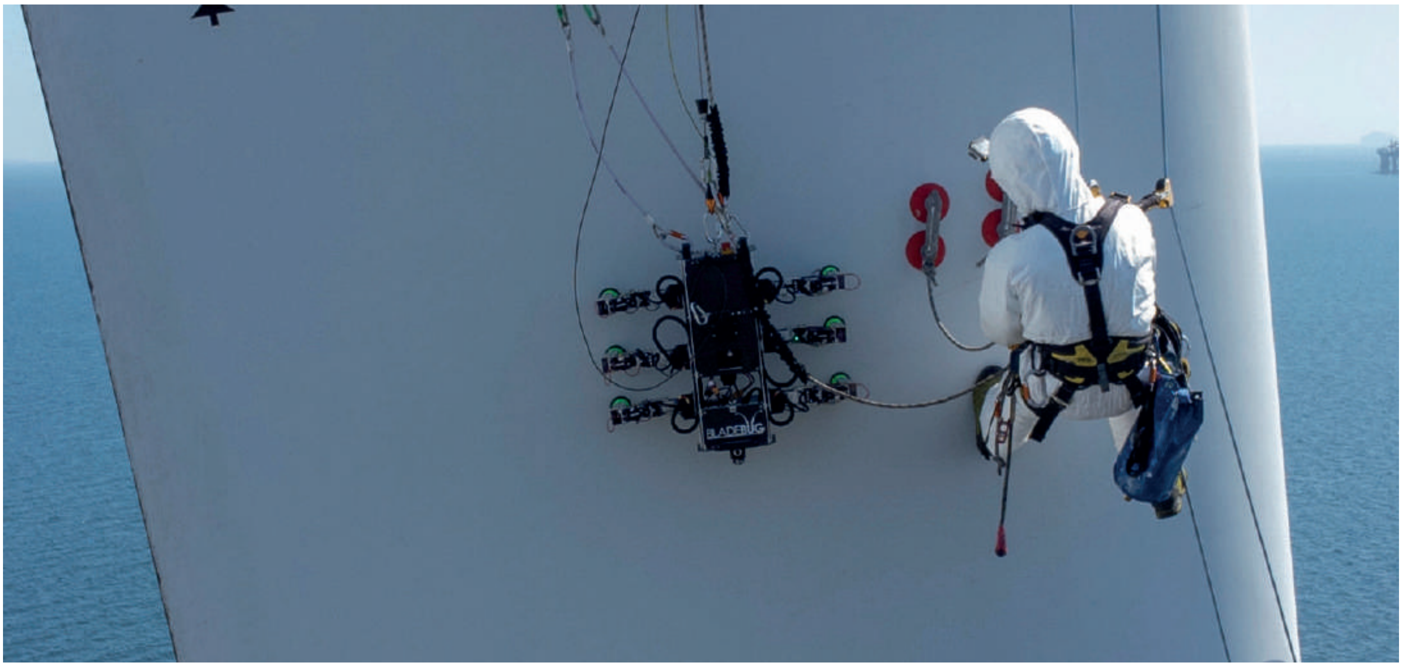


Figure 10. Using an ex-service blade to text the control system of the BladeBUG legged robot. (Source: ORE Catapult)

3. Operational Testing

Operational testing takes an autonomous system which has proven its functionality and places it in an environment that very closely replicates the intended operating environment. The purpose of this level of testing is to prove the functionality of the system in isolation, without any potential interactions it might have with other systems or operations that might be present in the field.

For some systems, there may be regulatory hurdles for carrying out testing at this level and beyond. This necessitates the creation of specific areas or zones within which systems can be trialled (e.g., Figure 11). These areas may have relaxed regulations or specific consents in place allowing for such trials. A key example of this is Beyond-Visual-Line-of-Sight operations (BVLOS) for unmanned aerial vehicles.

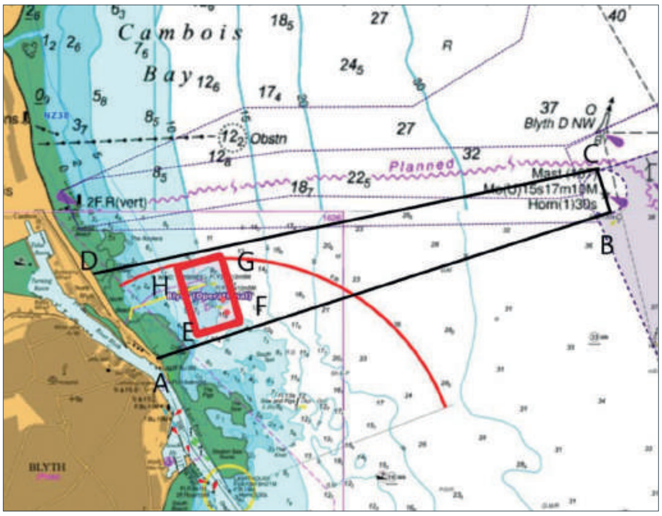


Figure 11. ORE Catapult's proposed offshore test area near Blyth, UK.

Figure 12. European Offshore Wind Deployment Centre at Aberdeen Bay Windfarm, UK. (Source: Vattenfall)

4. Pre-Commercial/Demonstration Testing

Pre-commercial and demonstration testing integrates the autonomous system with operations on a site. Some wind farms are designated as demonstration farms and have an obligation to test and demonstrate novel technologies, e.g., Figure 12. The only difference between this test phase and commercial operations is the length of time across which the system is expected to perform. This stage of testing can show how an autonomous system fits in with other operations, autonomous or otherwise. For instance, an autonomous underwater inspection vehicle may have to leave its dock, inspect an asset (potentially whilst there are manned diver repair operations ongoing), liaise/share data with a surface vessel, and then return to base. This type of testing will provide potential customers with maximum confidence that the system will not only function as intended but it will do so in harmony with existing commercial operations.

Overall, testing and demonstrating autonomous systems at multiple, iterative stages achieves two fundamental goals:

- Showing the system developer what is working and what is not. The empirical evidence can be used to inform improvements to the system.
- De-risking the system for the next stage of development. Whether it is grant funders, investors, or customers that must have evidence of performance, testing is necessary at all levels to convince stakeholders that their engagement with the system does not pose a significant risk.

5. Prototyping

When testing any technology, it is often important to be able to rapidly iterate on designs. In autonomous systems, the robotic hardware and the autonomous software are inextricably linked. It is likely in the process of developing RAS technology, that shortcomings in the hardware impact upon the ability of the autonomous aspects of the technology to function as intended. Take an autonomous surface vessel as an example. The autonomous control system will rely on inputs from an array of sensors taking in environmental data about the devices surroundings. If the sensors are incapable of capturing enough detail to correctly identify/map surroundings, then the control system might not perform as intended. It may be the case though, that this is not uncovered until the device is being tested in a real environment. At that point it is important to be able to rapidly iterate on the prototype device so as not to hold up development of the rest of the system.

6. Function Testing

Once a RAS prototype has been created, it must undergo significant function testing to verify the capabilities of the technology against the methodology. An important distinction to employ in the function testing of RAS vehicles for offshore wind farm applications is the initial manoeuvrability of the platform in isolation of its intended operation. The navigational proficiencies of the platform are of vital importance to its eventual applicability in the harsh offshore environment and should form a significant portion of the function testing. This may involve individual testing of numerous subsystems that facilitate movement in a range of scenarios. Once satisfied, the platform can then be utilised to test the capabilities of the payloads that enable the implementation of inspection or manipulative tasks. This is evident in the development of a robotic crawler, such as BladeBUG which has undergone functional testing at ORE Catapult's facilities in Blyth (see Figure 9). This system is designed for wind turbine blade inspection, maintenance, and repair. As part of the programme of function testing, the robot had to test several progressive scenarios of its walking gait before the inclusion of its sensing hardware.

7. Test Methodologies

It is important before undertaking a testing regime to have a definitive testing methodology so that outcomes of the testing can measured against their desired application. There may be distinct methodologies for individual systems or subsystems included in the robotic platform. There will be several generalised tasks that a RAS system or subsystem will be expected to achieve as part of an overall test plan. These tasks should be prioritised based on their cruciality to the system's function, implementation, and the associated dependences on other tasks. Within these will be individual acceptance criteria that again can be prioritised in terms of importance. Finally, there will be measurable "critical to quality" elements that can be quantifiable in terms of desired tolerances. Once these have been defined a definitive testing procedure can be formulated with appropriate scheduling of activities and scheduling of supply; see Figure 13.

Specific methodologies of testing may be more applicable depending on the goals, levels of prioritisation and structure of the testing team. Traditional "waterfall" approaches [24] may be more applicable to simpler test projects where aspects of development are predictable. Whereas, a more flexible "Agile" style methodology (e.g., Scrum) may be more appropriate for long-term, novel developments with a notable degree of prioritisation that may encounter frequent changes to requirements [25].

Figure 13. Test Plan Methodology for RAS System/Subsystems.

Figure 14. UAV demonstrating autonomous perching. (Source: ORCA Hub)

B. Simulation-Based Testing

Simulation-based testing uses computational models of a system to conduct verification and validation within a synthetic, rather than physical, environment. The prototype under test in physical testing is replaced by a virtual prototype in simulation-based testing. The virtual prototype can then be tested within the synthetic environment, in a similar manner to a physical prototype being tested practically (hence the term "Digital Twin" is sometimes used). This approach is known as virtual engineering [26], [27]. Simulation has a number of advantages compared to physical testing.

1. No materials or manufacturing processes are necessary to build virtual prototypes, so costs are reduced.
2. It is often possible to perform huge numbers of "runs" of a simulation in much less time than physical testing, so efficiency of testing is improved.
3. Simulation-based testing does not require the use of physical spaces, so the requirement to mitigate hazardous tests is eliminated.
4. It is easier to examine extreme, dangerous, and unusual scenarios during simulation-based testing. For example, an autonomous surface vessel could be tested during a detect-and-avoid manoeuvre in gale-force wind and sea conditions using simulation-based testing.

An obvious weakness of simulation-based testing, however, is that the results of the testing are only as good as the simulation models on which they are based. This applies to both the virtual prototype and the environment model. For example, if the gale-force winds mentioned earlier do not include gusts of different strengths, then the results drawn from the simulation may not be valid for the envisaged scenario. For this reason, the simulation software itself should be verified and validated. Finally, a hybrid approach to testing that combines elements of both physical and virtual aspects can also be used. Such "hardware in the loop" techniques [19] provide a useful bridge between physical and simulated worlds, often combining benefits of both.

C. Software Testing

Software testing can be used to examine software components within an autonomous system. In most existing autonomous systems, the high-level autonomous decision-making systems are made using software programmed in programming languages such as C++, Python, or Java. Software of this kind can be verified with respect to requirements at the system level using integration testing, or at the component level using unit testing. Software tests can be automated and integrated into the build process so that tests are performed automatically during development.

Regression testing can be used to ensure that recent changes to the software systems have not introduced errors. Additionally, software testing can be used to determine performance and user interface efficacy, and for V&V of models during the design and development processes, e.g., MATLAB models of system components. The benefits of such testing are that it is lightweight and easy to deploy; the drawbacks are that, for autonomous systems, guarantees of behaviour can be quite weak where test coverage is problematic. For example, assessing the "coverage" of testing for an adaptive component, dependent on a complex and partially known environment, is extremely difficult [28].

D. Formal Methods

Formal methods [21] may also be used to generate evidence for V&V. Such methods allow precise, mathematical descriptions of both computer systems and their requirements to be produced so that they can be analysed. The mathematical nature of these descriptions allows mathematical proofs to be generated. These proofs may show that the system always satisfies its requirements or may highlight instances where it does not. This process is often called *formal verification*, and can be applied to software and hardware systems, including communications protocols, abstract algorithms, security systems, biological systems, and many more [29]. The basis of formal verification in mathematical proof gives very strong guarantees about behaviour; this is not without cost (formal verification is time consuming) or problems (faithful models of the "real world" are impossible). Whereas formal methods provide a high level of certainty that requirements have been met, they are not suitable for every verification and validation task. Formal models can be difficult to construct and require expert knowledge. Automated formal methods such as model checking can be limited in their application by the so-called "state-space explosion" in which there are too many states for the model to be exhaustively analysed. Therefore, an effective V&V strategy will use several different techniques, including formal methods, in order to efficiently and effectively analyse the system at a sufficient level of detail.

Figure 15. Offshore wind turbines and substation. (Source: iStock)

E. User Acceptance Testing

User Acceptance Testing (UAT), sometimes also termed User Validation, can be used as part of validation of a computer system to determine whether the users' requirements have been met. UAT involves examining the system from the users' perspectives to determine that each requirement has been satisfied by a system [30]. For example, for an autonomous surface vessel, the UAT may include questions about whether the vessel's different functions (e.g., effective path-planning and collision avoidance) meet the users' requirements or not. As the complexity of autonomous systems increases, it may be useful to utilise techniques from Human-Robot Interaction to determine whether the system satisfies more subjective requirements concerning perceived safety, transparency, or rationality [31].

F. Runtime Verification

Runtime Verification [32], sometimes called Runtime Monitoring, can be used to ensure that the system is behaving correctly at runtime, i.e., during operation. Runtime verification works through the use of software monitors which analyse the real-time RAS behaviour [33]. Any deviations from expectations or design specifications can be reported to the operator and/or the autonomous system itself, so that the operator/system can try to assess and mitigate the error. Runtime verification takes into account the complexity of autonomous systems and the possibility of unexpected behaviour within complex environments, aiming to compensate for this by allowing the system and the operator to take measures that ensure continued safe and reliable operations. For example, a run-time monitor could be used for an autonomous surface vessel to monitor the distance between the vessel and other vessels. If this distance becomes too low, then the monitor will alert the operator and the autonomous system. The operator could use this information to take over control of the autonomous system, and the autonomous system could determine that the current control system is not working effectively and therefore another control system could be used instead.

Note that this runtime monitor is separate from the control systems being used by the autonomous system for routine navigation. This separation enables the runtime monitor to be developed and implemented separately from the control system to provide increased reliability. Such monitors can also be verified using formal methods and can be designed to monitor specific requirements and design specifications directly. Furthermore, runtime monitors can be used as a part of an explainable, self-aware autonomous system to provide higher levels of reliability and transparency.

G. Corroborative Verification And Validation

Since all representations of a real scenario are necessarily approximations, V&V is not a perfect process and cannot guarantee correct operation of an autonomous system. Even with physical testing, the test scenario will never be the same as a deployment scenario. As a result, our confidence in the system is dependent on several factors including:

- the V&V technique used,
- the amount of effort spent doing V&V, and
- the strength of the arguments of the system's reliability.

One way to increase the level of confidence we have in V&V results is to use multiple techniques to analyse the system. Different V&V techniques have their own strengths and weaknesses, so by applying a number of V&V techniques we are more likely to be able to accurately determine the system's adherence to design and requirements, and increase our confidence in the results of V&V.

V&V techniques include those covered earlier in this section: physical testing, simulation-based testing, formal methods, and so on. These techniques can be described in terms of their underlying system description and requirement encoding. For example, in the case of formal methods, the system is modelled as an abstract mathematical model of the behaviour of the system.

Figure 16. Offshore technician accessing wind turbine. (Source: iStock)

The requirements are encoded in a mathematical logic language, e.g., "□distance(other_vessels,safe)", meaning that it is always the case (□) that the distance to other vessels is safe, i.e., safe separation between vessels is maintained [34]. In simulation-based testing, the system description can be more detailed. The requirements are typically modelled as assertions within the simulation code. For example, the previous requirement concerning safe distances can be modelled as an assertion, "distance(other_vessels) ≥ 10 m", which states that the distance to other vessels must be at least 10 m. If this requirement is violated within the simulation, then the assertion is violated, and this can be recorded by the simulator for later analysis. In physical testing, the system description is the experimental setup of the autonomous system within its test environment, and the requirements are typically defined as test requirements written in English, e.g., "the vessel should maintain a distance of at least 10 metres from other vessels." If these requirements are validated, then this can be noted by experimenters for later analysis.

Whenever we use a V&V technique to analyse a system, we generate evidence. This evidence can be compared using an approach called Corroborative V&V [22], and the results of this comparison can be used to improve the accuracy of the system and requirements descriptions. The aim of corroborative V&V is to allow different V&V techniques to corroborate each other, in much the same way that witnesses can corroborate each other in a court of law. In the ideal case, all techniques will reach agreement. However, even if this cannot be achieved, the process of corroborative V&V is intended to improve the quality of the evidence generated by the various V&V techniques, and therefore increase confidence in the V&V process holistically.

Corroborative V&V can be explained by continuing the example of an autonomous surface vessel described above. Suppose that we choose to use two V&V techniques: physical testing and simulation-based testing.

During physical testing an autonomous surface vessel is manoeuvred around a stationary surface vessel on calm waters. It is determined that the minimum separation between the two vessels was 9.4 m, and therefore the requirement concerning a 10 m separation has been violated. When the same manoeuvre was conducted in simulation the minimum separation is found to be 11.0 m, which satisfies the requirement. The evidence generated by the two V&V techniques is not corroborative, as in one case the requirement is found to hold, and in the other it is not.

We can conclude that there must be a difference between the way the system or the requirement is described. In this case, the requirement is simple and is expressed in terms of the separation between two vessels in both V&V techniques, so it is unlikely that we can account for the non-corroboration from a difference in the way the requirement was modelled between the two techniques. The other possibility is that there is a difference between the way the system is described in the V&V system descriptions.

In this case, it is found that during physical testing there was a prevailing wind of 5 metres per second, which was not included in the simulation. The simulation is then modified to include the prevailing wind. The new version of the simulation reveals that the minimum separation between the two vessels is actually 9.9 m. Whereas the evidence generated is still not corroborative, the disparity between the two has now been reduced (from 1.6 m to 0.5 m), and the accuracy of the simulation system description has been increased. It is possible to compare again the system and requirements descriptions in order to further improve them and, hopefully, approach full corroboration between the two V&V techniques.

This slightly contrived example demonstrates corroborative V&V for two V&V techniques, but the approach can be extended to three or more V&V techniques and has been used in realistic scenarios [22]. The approach is summarised in Figure 17.

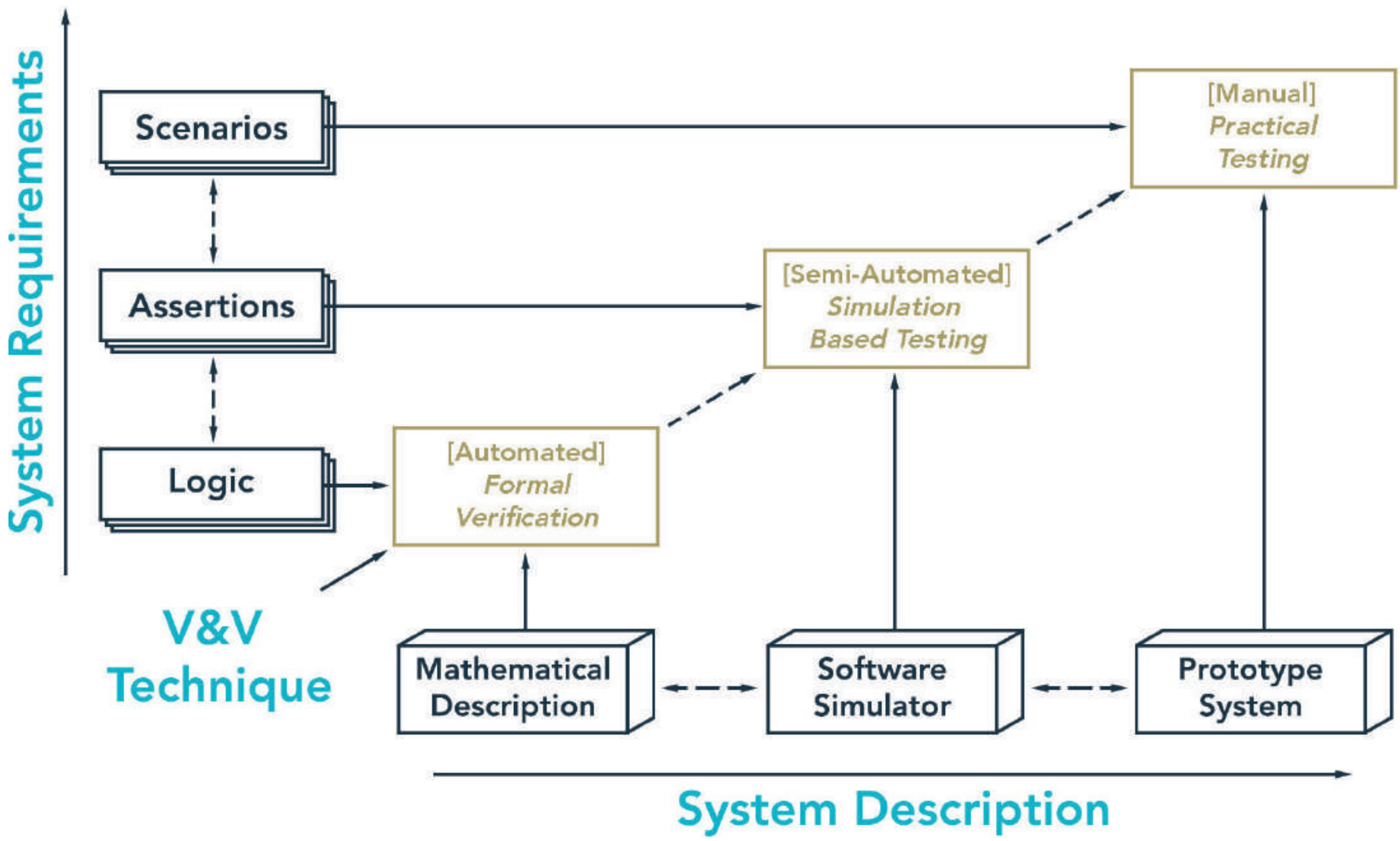


Figure 17. Corroborative V&V with three V&V techniques [22]

4. Designing for Verification and Validation

This section describes some recurring themes to be considered in the design of autonomous systems that aid the application of stronger, and more comprehensive, verification and validation.

A. Requirements Gathering

The use of precise, clear, and unambiguous requirements is essential in the development of autonomous systems. System requirements may come from various stakeholders:

- The end-user of an autonomous surface vessel may be a provider of offshore renewable energy that would like to use the vessel for remote monitoring of assets such as wind turbines.
- The potential operators of the vessel: they may wish to be able to monitor sensor output in real-time in order to have a better understanding of the vessel's condition and situation.
- Maintenance engineers. "Consumable components should be easy to locate and replace," is a typical requirement.
- Investors in the business producing the vessel may also have requirements, e.g., "the cost must be lower than a certain threshold in order to ensure profitability".
- Government regulators will also have requirements of the system to ensure that the system will be safe in its operations and will not cause a hazard to other marine users. (An overview of some of the relevant regulations is given in the Appendix.)

Techniques from requirements engineering can be used to elicit requirements from both users and stakeholders, and formulate these requirements in a clear, explicit way [35]. Requirements can be decomposed into sub-requirements as needed. For complex systems with large numbers of requirements it may be useful to employ a requirement engineering software tool such as IBM's Dynamic Object Oriented Requirements System (DOORS) [36].

Requirements may also be derived from realistic and clear use cases: providing detailed scenarios to stakeholders may allow them to better understand and state their requirements. For example, a case study, such as that presented in Section 5, could be given to stakeholders during the requirements elicitation phase.

The requirements for the validation and verification process are influenced by a multitude of sources but will still be dictated overall by the direct needs of the "customer." The general context of a "customer" for a technology is typically the end-user for the product, which will be the wind farm owner/operator. However, to develop a robust set of customer requirements, other influences and stakeholders are important (see Figure 18):

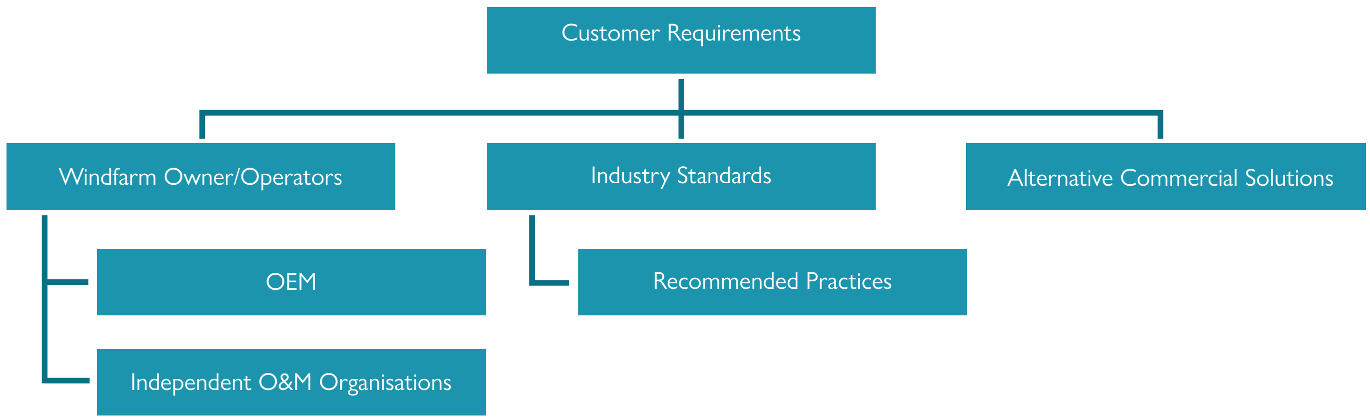


Figure 18. Customer Requirement Drivers.

- **Wind Farm Owner /Operator** – Requirements are based on the desired and intended uses of the technology by the consumer. The final specification will be driven by both technical and commercial considerations. For the case of offshore wind these requirements are also imposed by the warranty conditions indicated by the Original Equipment Manufacturer (OEM) or the insurance implications of carrying out work on a wind turbine component or asset. Third-party O&M service providers may also intend to exploit RAS solutions.
- **Industry Standards** – Industry standards intend to define the minimum specifications products and services should adhere to, extending to the usage of RAS technology by the customer. Standards can be published by accreditation and certification organisations (e.g., DNV GL), national standard bodies (e.g., BSI Group) or through industry collaborations. For applications where there is a lack of industry standards, recommended practices provide guidance.
- **Alternative Commercial Solutions** – Existing commercial solutions may be available to the customer and already define how the tasks are already carried out, or even define existing customer requirements. An assessment of existing technology should be completed to ensure customer requirements are developed as absolute requirements and not relative requirements based on the constraints of existing technology.

The primary stakeholders are the owners and operators of individual wind farms. They will have the overall say on when, where, and how a RAS can perform actions on their site. These requirements can vary from wind farm to wind farm. There is no singular regulatory body for the offshore wind sector. To avoid overall regulation wind turbine manufacturers and operators have set up individual organisations to combat areas of concern. For instance, the Global Wind Organisation provides training standards that technicians and training providers are required to adhere to, in order to perform work at onshore and offshore wind farms. Similarly, the G+ Global Offshore Wind Health and Safety Organisation attempts to drive good practice and promote world-class safety performance across the sector [37].

Other key regulatory stakeholders include the regulatory body for the vehicle domain. These regulatory bodies impart direct restrictions on how an autonomous vehicle can operate, with BVLoS permissions a key issue for both the aerial and marine domains. Weight restrictions of Unmanned Air Systems (UAS) are another key consideration as above the limitation of 25 kg, according to UK airworthiness regulations [38], airworthiness approval is required. The current regulatory advice is that there are currently no, and will foreseeably never be, UAS that meet the definition of being fully autonomous [38]. Instead advanced UAS systems can be defined as highly autonomous and will foreseeably always require a level of human input. There are many international marine conventions that restrict unmanned marine vessel operations. The Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) [39] is the most contentious due to overall qualitative compliance contained within, written for a human operator to be “physically present on the navigating bridge” [40]. Seabed and ocean floor activities are managed and controlled by the national authority, e.g., the Crown Estate in the UK.

“The primary stakeholders are the owners and operators of individual wind farms. They will have the overall say on when, where, and how a RAS can perform actions on their site.”

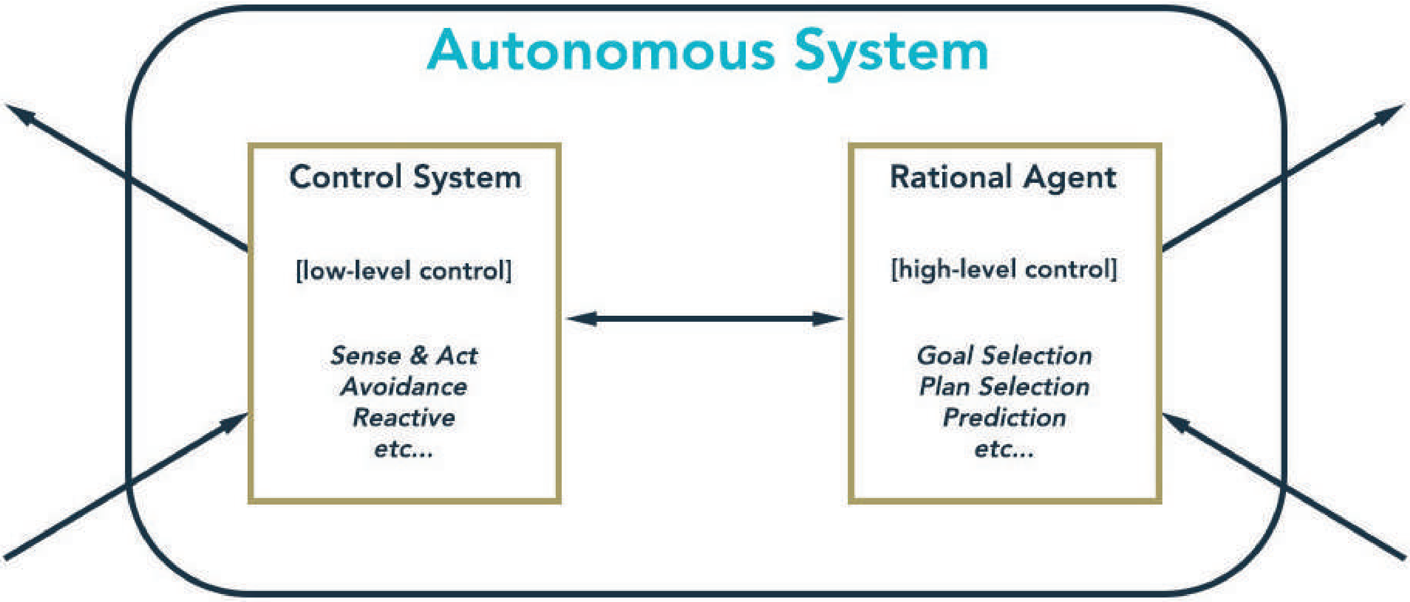


Figure 19. A hybrid autonomous system.

B. Separation Of Autonomous Decision-Making

Many autonomous robotic systems use sensors to gather information, control systems to manipulate actuators to effect motion, combined with a decision-making procedure to decide what to do and when. In some cases, the decision-making may be contained within the control system which maps sensor inputs to actuator outputs. In many cases it is advantageous to make the decision-making procedure a separate unit that only makes discrete decisions based on discrete data. For example, the autonomous systems can choose to do X if a particular condition is true, and Y otherwise. An autonomous system with a separate, discrete decision-making system is known as a hybrid autonomous system (see Figure 19). The advantage of this kind of separate decision-making systems is that such discrete systems are more amenable to the use of formal methods which can exhaustively analyse the decision space of the decision-making process. In addition, such decision-making processes can be based on rational agents, which can decide what to do based on their beliefs, desires and intentions [41]. Since their decision-making process is based on a natural understanding of autonomy, their behaviour is straightforward to explain to an operator. In particular, the key new aspect of "autonomy" concerns understanding why a system makes the decisions it makes and rational agents capture the motivations and intentions in a clear form.

The use of model checking, a formal method, has been used many times to exhaustively analyse the behaviour of autonomous decision-making systems for a wide variety of applications [42].

Furthermore, separating the decision-making from control systems, sensors and actuators allows those systems to be analysed separately. For example, control systems can be analysed using formal methods, simulation, or mathematical analysis; sensors and actuators can be stress tested using physical or simulated test rigs. Analysing each component relative to its own requirements reduces the complexity of V&V and improves confidence in the results.

C. Transparency Of Behaviour

During V&V of an autonomous system it is imperative to be able to understand and explain the behaviour of the autonomous system at every stage in its operation. This can help to determine whether requirements and design specifications are satisfied and can help provide a convenient method of demonstrating to certification agencies that the system complies with regulations. Furthermore, an explainable autonomous system [43] greatly increases the usefulness and trustworthiness of the system for operators. The separation of the decision-making component described above can enable the autonomous system to explain itself in terms of discrete, logical decisions.

The use of a rational agent paradigm [41] is also helpful, as the agent can explain its behaviour in terms of its beliefs, desires and intentions. For example, a rational agent for an autonomous surface vessel could report that, “I intend to return to base as I believe my fuel level is at a critical level, and I have a desire to ensure that fuel levels never drop to zero.” [44]

D. High-Fidelity Simulations And Virtual Engineering

Autonomous systems are often complex and can be difficult to understand and interpret. Therefore, it is essential that potential risks and hazards are identified effectively before they occur in real-life situations involving personnel and assets. The use of high-fidelity simulations can help with this de-risking, and enable developers, regulators, and potential end-users to explore the use of autonomous systems in a safe environment. High-fidelity simulations contain accurate physical models of the systems and incorporate computational approaches such as finite element analysis, flight dynamics modelling and computational fluid dynamics to build accurate virtual prototypes of the systems being analysed [27]. Such simulations can also employ three-dimensional visual models which provide a natural and persuasive representation of systems and scenarios. Furthermore, these simulations can be used throughout the design process to de-risk the development process and reduce the costs of real-world prototyping and experimentation [34]. This overlaps with the aims of simulation-based testing and virtual engineering described in Section 3-B.

E. Expect The Unexpected

Until now, robotic systems have been mainly deployed in environments that are either controlled and well-understood, such as factory production lines or controlled warehouses, or in situations where few safety issues arise either due to lack of capability (e.g., robot vacuum cleaners) or lack of human interaction (e.g., robots contained/constrained). Furthermore, the sub-systems involved have also been quite well analysed and understood. However, we are now facing (at least) two issues for the application of offshore renewables: autonomous robotic systems are being deployed in much less well-known environments (e.g., marine environments) and the behaviour of AI sub-components is increasingly dependent on the environmental interactions they encounter.

These new dimensions lead to several issues:

- We cannot always predict every hazard/issue beforehand;
- AI components cannot be guaranteed to have certain, predictable behaviour; and
- Physical conditions will increase the likelihood of subsystem failure.

In other words: things will go wrong; things will break; and we cannot predict all of these. Consequently, significant thought must be put into mechanisms/techniques addressing the following:

- How do we recognise anomalies, unexpected behaviours, or behaviours beyond the safe/certified envelope?
- When we recognise such behaviours, can the system work out why this happened and, whether it can or not, what to do about it?
- Can we design in fail-safes (e.g., IEEE P7009, see Appendix), error-handling procedures, fault-tolerance, health management, etc., that can cope with many of these situations?
- How can we verify these procedures, especially given that we cannot fully model the environment?

These are all key issues that need to be assessed and analysed.

F. Increasing requirements

Traditionally, the requirements on systems, be they from users, operators or regulators, have primarily concerned functionality and safety. The development of increasingly autonomous systems has led to an extension beyond these, still essential, categories. Since the core new aspect of autonomous systems is that software will now make decisions, and even take actions, then there is increased emphasis on the behaviour of this software. Consequently, there are a range of categories, beyond function and safety, that will also be considered. We will not describe all possibilities here, but instead provide two examples to show the (very) different aspects that might need to be taken into account within V&V: security and ethics.

Figure 20. Offshore wind farm. (Source: vschlichting/AdobeStock)

Cyber security is an increasing concern for complex, cyber-physical systems, and is especially an issue with autonomous systems that might contain quite complex AI components [45]. The ability of an attacker not only to intercept (or inject) communications, but to potentially take over control of an autonomous robotic system, is unsurprisingly a key issue. Consequently, security requirements are being incorporated into the system requirements that must be verified. These not only cover who/what can take control of systems (c.f. levels of autonomy above) but who has access to data and communications. The requirement to (at least) have non-trivial levels of encryption is common, but there are many attacks where encryption is not enough. A further complication is the use of "black box" AI components, such as deep/reinforcement learning [45], within autonomous systems. A sophisticated attacker can insert data/events into the stream that such components are observing, and then drive an adaptive system towards unexpected/unwanted behaviours. Consider a simple example whereby communications to/from a remote-controlled autonomous surface vehicle (ASV) are intercepted, mimicked, or modified. In such cases, an attacker can potentially take control of the ASV (as it assumes the commands come from the operator) and so cause a wide range of problems.

As autonomy increases, so the responsibility for safety-critical, and even life-critical, decisions move to the system's software. We might well have been through a range of V&V techniques in order to assure safety, and even security, of our system [22].

However, as highlighted above, we must "expect the unexpected" and, since not all scenarios can be predicted, the autonomous system software must make key decisions "on the fly" or at least within short timeframes. Although this seems quite detached from the theory being discussed, these situations can rapidly move on to ethical considerations.

Clearly, minimising accidents is a priority. However, in a complex and unpredictable world we can never guarantee this. So, if an accident is inevitable but was not predictable, what should the autonomous system do? Increasingly, the option to "do nothing" is unacceptable and we quickly move to ethical issues such as the famous "Trolley Problem" [46]. Imagine an ASV that has an emergency that will result in the vessel crashing into either one of two offshore objects, a wind turbine and a manned cargo ship, and also let us assume that it has lost all external communications. The ASV must (autonomously) decide whether to crash into the turbine or the cargo ship. In this example, the autonomous system may have been designed to avoid crashing into objects, but we cannot predict all the problems that can occur in its domain of operation, e.g., a choice between crashing in to one of two different objects. Therefore, the autonomous system might well be left with an ethical dilemma and resultant actions in such situations must be described (and verified). This type of example might seem far-fetched, but ethical aspects of robotics are increasingly an issue, even leading to a British Standard (BS 8611) [47] outlining some of the ethical hazards.

5. Case Study: Design of an Autonomous Service Operation Vessel

Service Operation Vessels (SOVs) are used to support offshore wind farms far from the shore, so that long transit times are avoided. Access to wind turbines is provided via a motion-compensated gangway. Royal IHC is currently developing a next-generation SOV with improved station keeping, workability, safety, and efficiency capabilities. Besides designing and manufacturing the vessel, IHC Digital Business Systems (part of Royal IHC) is developing a system that will enable the autonomous operation of the SOV. Smart integration of the systems on board provides the ability to navigate autonomously through the wind farm, followed by automatic connection of the gangway to the turbines. This work is supported by a subsidy from the Dutch Ministry of Economic Affairs, as part of the innovation program TKI Wind Op Zee [48], because of the potential reduction in energy production cost in offshore wind farms.

The first version of the autonomous system, "Mission Master", is designed to operate at PACT level 4a: at this level, the system chooses and performs actions after the operator has granted approval (PACT levels are described in more detail in Section 2-B). With this system, Royal IHC aims to increase the safety, efficiency, and crew comfort. The first step towards autonomy is to merge the tasks of both the gangway and Dynamic Positioning (DP) operator into a workflow that can be supervised by one person. Royal IHC has already developed a similar concept for the dredging industry, with the one-man operated bridge for trailing suction hopper dredgers. This concept combines the tasks of the dredge operator and the navigator to be operated by one person. Future steps on the road to autonomy also include efficiency gains in the engine control room.

A. Autonomy Design Process

The design process of the autonomous SOV started with the drafting of functional requirements, so that the capabilities of the system could be determined (requirements gathering is described in Section 4-A). For example, one of the requirements is that the Mission Master should be able to assess the workability and the station-keeping footprint of the vessel in order to be compliant with the rules established by DNV station keeping assessment level 3, as stated in DNVGL-ST-0111 [49]. In this way, the Mission Master can ensure that autonomous operation within the wind farm is only started if it is safe to do so. A second example of a requirement is that the autonomous SOV must be able to transit between turbines at least as fast as an operator controlled SOV would do. For these requirements the main stakeholder will be the vessel owner, who aims to conduct a safe and efficient operation.

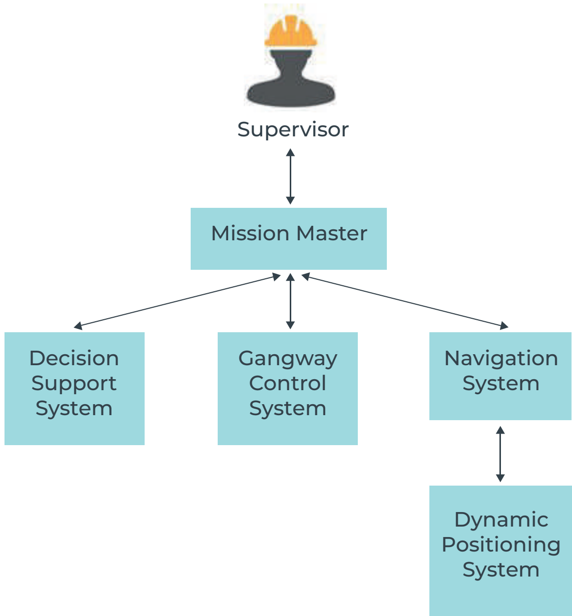


Figure 21. The SOV hierarchical autonomous system.

A hierarchical autonomous system has been designed to control the vessel and the equipment on board. During the design process the ambition was to create a modular system that would be structured and easy to maintain. Requirements were translated into functional specifications that were assigned to systems and sub-systems. At the top of the hierarchy is the Mission Master, this system interacts with the supervisor and is responsible for the top-level control on board. Given a set of turbines to visit, the Mission Master determines the optimal path and uses the Decision Support System to verify that the mission can be executed safely.

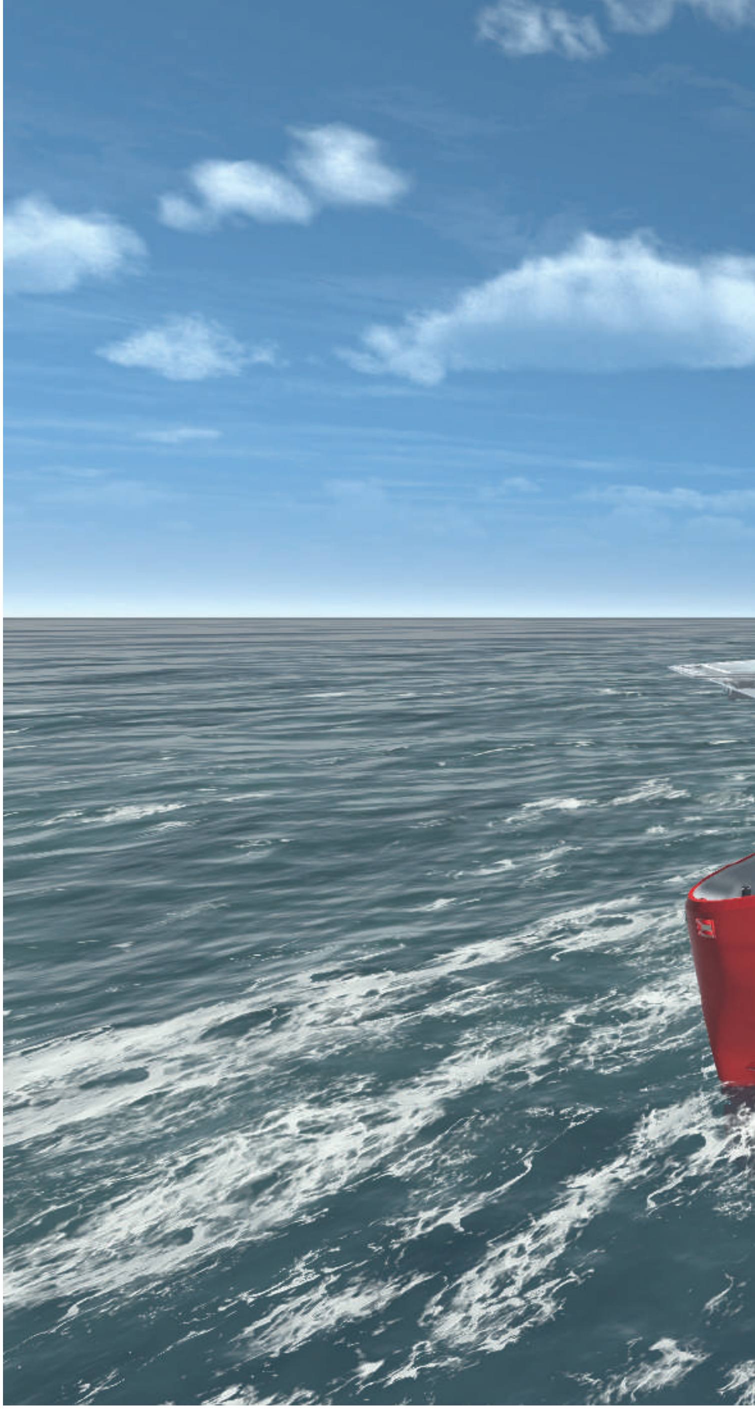
The Mission Master commands the Gangway Control System and the Navigation System lower down the hierarchy. The Gangway Control System manages control of the gangway, the Navigation System guides the vessel through the wind farm and controls the Dynamic Positioning system. Both systems have clearly defined responsibilities, and they communicate with the Mission Master. In this setup the high-level control is separated from the low-level control. The high-level control systems are designed as finite-state machines which enables that the actions of the system are predictable for one who has studied the system well, therefore creating transparency of behaviour.
In the next section it is described how Simulation-Based Testing is used in the verification and validation process.

B. Simulation-Based Testing

A simulator environment has been created to verify and validate the performance of the autonomous SOV. In this environment the SOV can be representatively tested within any wind farm configuration and under adjustable wave, wind, and ocean current conditions. The environment uses a physics engine to simulate the weather and six degrees of freedom of the vessel's motion, replicating the inputs and outputs of the software-based autonomous systems in real time. In addition to simulating the physics of the process, a 3D viewer can be used to get a graphical representation of the SOV and its surroundings.

The actual software developed for the Mission Master and the Navigation System can directly interface with the simulator environment, allowing the integration of several systems, including the Dynamic Positioning system software which controls the thrusters of the simulated vessel. Likewise, the Gangway Control System and associated gangway hydraulics are dynamically simulated. By utilising this setup, it is possible to test the interaction and performance of the different systems that provide the autonomy on board the SOV. An additional benefit of the setup is that different weather scenarios can be instantly created, where one would have to wait for the right weather conditions when performing a fullscale physical test at sea.

With all systems responsible for the autonomy in place, the operation of the Autonomous SOV can be simulated and analysed. This enables comparison of the operation's efficiency with the efficiency of similar SOVs deployed offshore. By analysing measurements of the gangway landing and the transits between turbine visits, it becomes clear how the autonomous SOV performs compared to actual vessels in the field. An important metric for this comparison is the total time it takes to visit a set of turbines.



The safety of the autonomous SOV can also be assessed with the simulator. By analysing the simulated operation, it is determined if any dangerous situations have occurred. For example, the logged data verifies

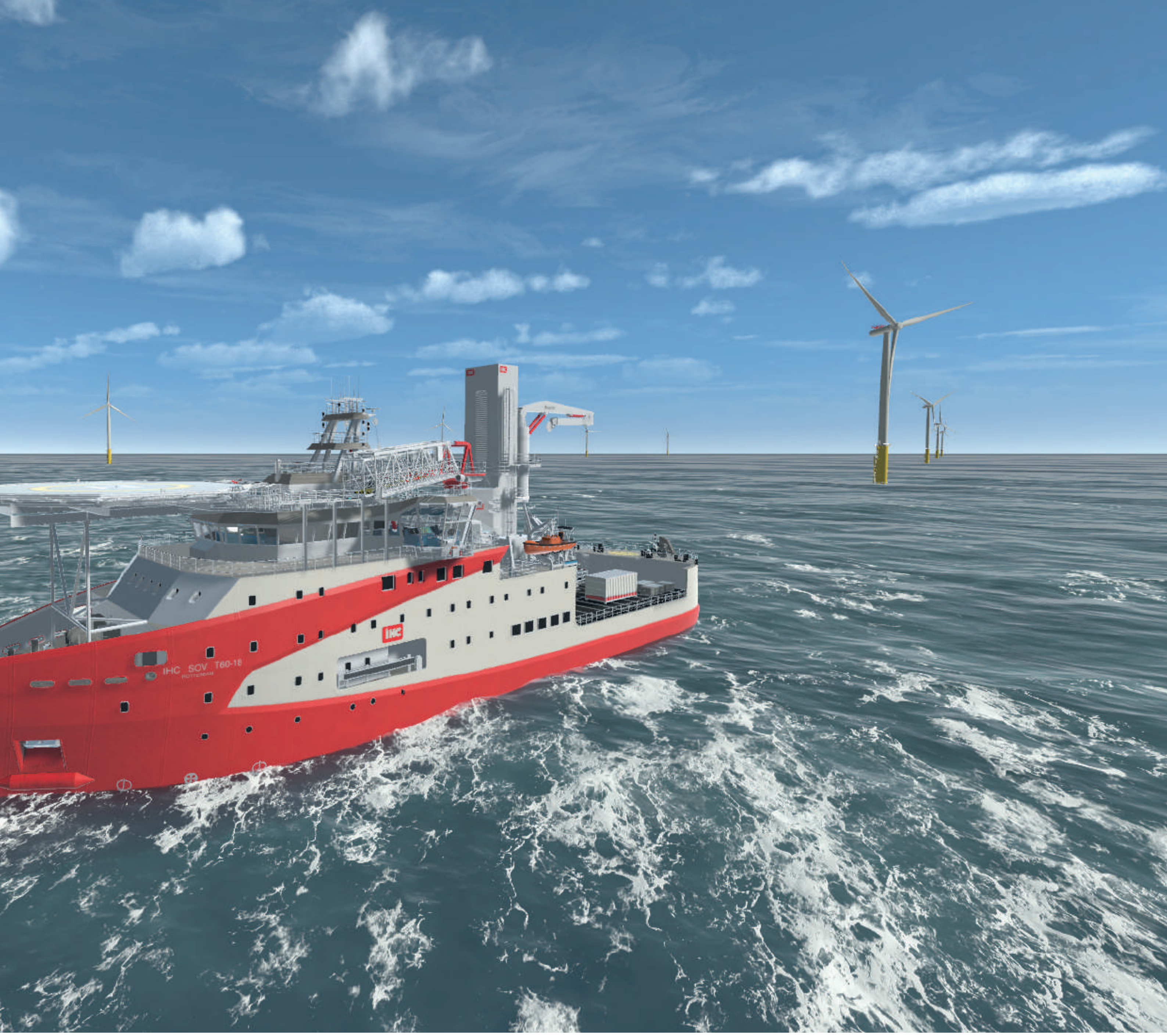


Figure 22. Autonomous SOV simulator environment. (Source: Royal IHC)

that the SOV has not entered any of the turbine's safety zones during the transit phase between turbine visits. Simulating the operation also provides insight into possible errors that may occur in the system. Therefore, endurance testing of the system in many different scenarios is performed to increase confidence in the robustness of the system before it is installed on board.

Another important goal of the simulator environment is to analyse the workability of the vessel. For this purpose, the simulator contains realistic models of the hydrodynamics, wind and current loads, gangway dynamics and thrusters. This makes it possible to perform workability assessments with six degrees-of-freedom time-domain simulation including gangway motion limitations and Dynamic Positioning station-keeping performance. In this way, the simulations meet the requirements set by DNV for station keeping at assessment level 3-site.

The simulator is built in a cloud environment, enabling flexible and easy access of the simulator setup from different locations. The simulator can be extended to a Hardware in the Loop (HIL) version [19], to include not only software but also the hardware components.

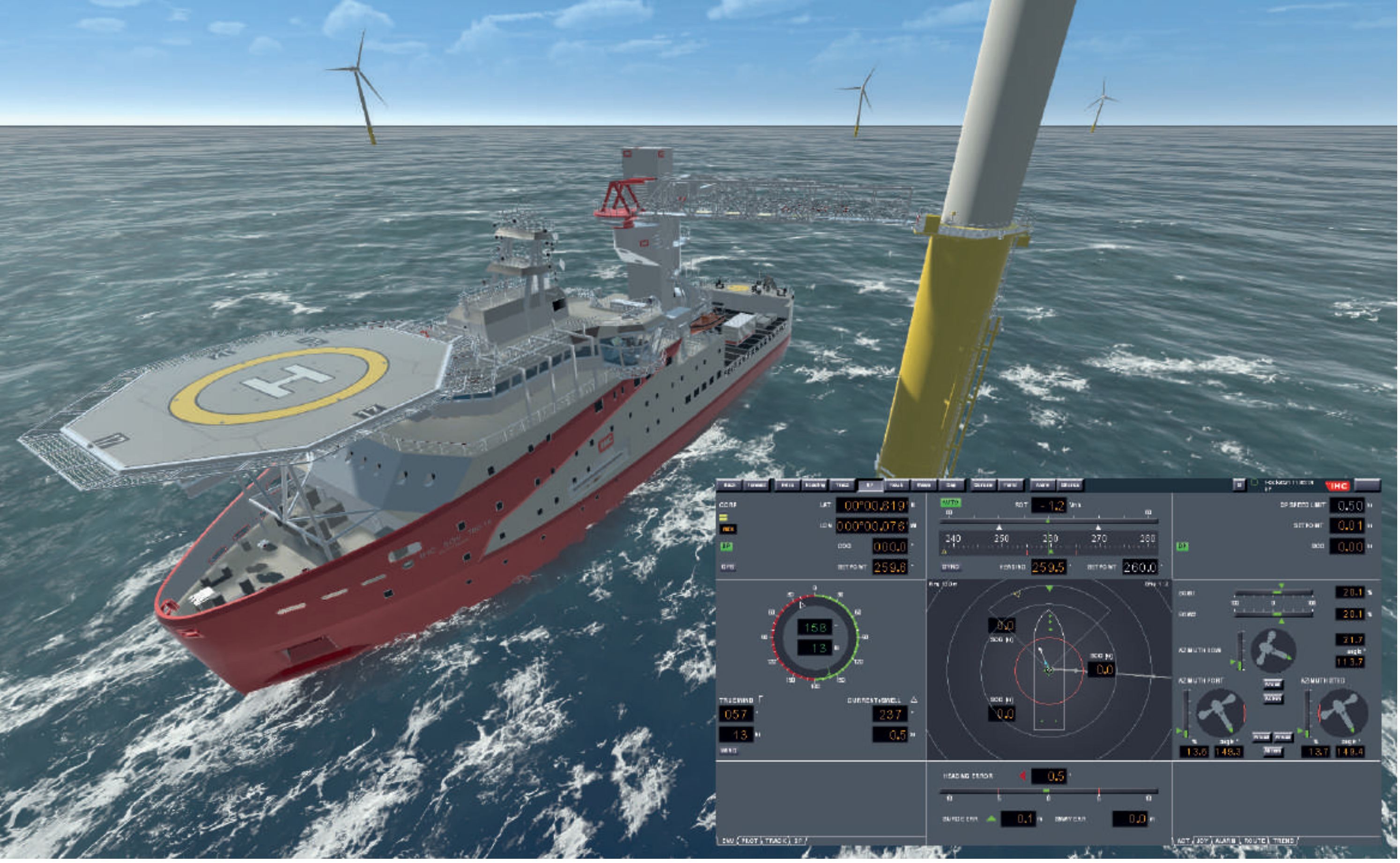


Figure 23. The simulator environment, showing the 3D viewer with the Royal IHC DP system overlay. (Source: Royal IHC)

The HIL simulator also makes it possible to test the hardware and network functionalities, allowing testing of Failure Modes, Effects and Analysis (FMEA) [50] of sensors, networks, and other hardware components. Furthermore, the simulator, implemented as a full copy of the on-board systems connected to a virtual vessel, makes the setup suitable for designing a user-friendly human-machine interface and for comprehensive user acceptance testing with operators. At a later stage, the simulator can be used to train the future crew for operational and maintenance purposes.

With the inputs and outputs being replicated a realistic testbed for the autonomous control system is established, however a simulation is never a perfect representation of the real world. To improve confidence in the system a second V&V technique was used. Physical testing was performed with a scaled version of the SOV, in a wave basin the seakeeping behaviour and dynamic positioning capabilities of the SOV were analysed under different wind, wave and current conditions. Results of these tests were used to verify if operational requirements could be met, and the measurement data has been used to improve the simulation models.

C. Summary Of The Case Study

Simulation of the full mission of the autonomous SOV in a realistic operational environment in real time makes it possible to verify and test the proper functioning of the autonomous system in many different scenarios. This applies to all levels, from component level to integrated system level. The simulator environment proves to be a useful tool in the design process of the autonomous SOV, the ability to integrally test the interacting systems has already led to many design improvements. Confidence in the system has been increased by using both Simulation-Based testing and Physical testing as V&V techniques. In 2020, the Mission Master reached TRL 6. At this level the simulator provides a relevant end-to-end test environment in which the system and the human-machine interface can be tested and validated against the corresponding requirements.

6. Conclusion

We have shown how a robust process of validation, verification, testing, and demonstration during the development and adoption of autonomous systems for offshore renewable energy is crucial for assuring reliability, cost-effectiveness, and safe operations. In the following sections we recapitulate the main findings of this study.

A. Validation Improves the Market Potential of Autonomous Systems

A robust validation process involves gathering and managing detailed requirements from the potential users of an autonomous system. This process defines the boundaries of acceptability within which the system must operate. By validating that the system meets these requirements fully, the development team will ensure that the autonomous system can undertake the missions required in an offshore wind farm.

Without a clear validation process accounting for the commercial and operational requirements for a system, autonomy will only be developed as a scientific interest. Fundamental research is essential and forms the bedrock upon which innovations can be developed. In creating an autonomous system with a purpose however, it must be developed towards the needs of the customer to ensure it is commercially relevant and can be deployed in an industrial setting.

Users should be engaged early in the development process, and continuously through the development lifecycle for the system to be properly validated against its requirements.

B. Verification Reduces the Adoption Risk of Autonomous Systems

A strong set of requirements means nothing if the developed autonomous system is unable to meet them. Verification is as important as validation in this regard, since users will need to see how the system performs to de-risk their adoption of autonomous devices. Using robust V&V methodologies as described in this study will give the greatest confidence to users of the autonomous systems that the system will perform as intended and required in all scenarios.

For field robotics (such as those deployed in offshore wind) the scenarios which autonomous systems can face are varied, complex and unpredictable. This increases the importance of using synthetic environments and techniques such as virtual engineering trials to improve the efficiency (and crucially the cost) of V&V activities. It is highly unlikely that the entire envelope of operational environments could be recreated in the physical environment but significantly more plausible in a virtual one.

“Without a clear validation process accounting for the commercial and operational requirements for a system, autonomy will only be developed as a scientific interest.”

C. Testing Activities Boost the Confidence of Autonomous System Development and De-Risks Further Demonstration

In technology development, it is crucial to de-risk progression. By undertaking testing of autonomous systems in representative but safe environments, unforeseen technical issues can be overcome easily and quickly. This enables more testing to be undertaken, with a more iterative approach. Offshore wind farms are far from shore, expensive to access and often have inclement weather conditions.

Complexity can be added incrementally, increasing the realism of the testing activities. This enables the developers of the autonomous system to quickly iron out teething issues and increase their own confidence in the system. All of this can be undertaking without the risk of a mission failure in an operational or commercial setting which could lead to a drop in user or investor confidence in the system.

A structured approach to TRL progression (see Section 3-A) improves the efficiency of the overall process by reducing the occurrence of costly failures or unforeseen challenges. When the system progresses to user-acceptance trials the technology developers can have a higher level of assurance there will be no teething issues during the trials which could lead to commercial or reputational harm.

D. Demonstration of Autonomous Systems Boosts Investor and Customer Confidence

As an autonomous system progresses towards completeness and commercial readiness, early adopters will want to ensure the system can perform the task(s) at hand. Often the best way to showcase the performance of the system is with a trial or demonstration in an operational or highly realistic environment. Whilst an operational demonstration may not evaluate performance in as many scenarios as a synthetic trial at earlier levels of development, it is very tangible and allows investors and other non-technical stakeholders to understand the behaviour of the system much more readily.

Demonstration is an important phase for the commercialisation of technology and can add significantly to the marketing potential. It does however contribute less to the development of the system itself as by this stage it will be largely finalised. Demonstrations are important for users to feedback on the performance of the autonomous system against their use cases and requirements stated at the outset, therefore forming an important part of the system's validation.

> *"Demonstrations are important for users to feedback on the performance of the autonomous system against their use cases and requirements stated at the outset, therefore forming an important part of the system's validation."*

E. Transparency and Explainability of Decision-Making Increases Confidence and Enables Verification and Validation

During its operation, an autonomous system will necessarily make many decisions concerning the successful completion of its mission. If the reasons for these decisions are made clear and are explainable the system can be said to be transparent in its decision-making. Transparency in individual decisions, as well as in the decision-making process itself, allows operators of the autonomous system to increase their confidence in the decisions being made as well as the overall trustworthiness of the system. Indeed, transparency may be relevant to other stakeholders. For example:

- Transparency to certification agencies may aid in the certification process.
- Transparency to regulators may aid in the development or refinement of regulations.
- Transparency to people or other autonomous systems in the vicinity of operation may aid in the prevention of accidents.
- Explainability of decisions made by the system may aid in offline analysis of those decisions by those wishing to improve the effectiveness of the autonomous system.

The use of transparency within autonomous systems also enables the verification and validation process itself, as systems that are clear in their goals and state can be verified using exhaustive techniques such as those used in formal methods.

F. Validation and Verification Are Crucial Throughout an Autonomous System's Life Cycle

The outcomes of V&V extend beyond proving that a system satisfies its requirements and design. A documented V&V process that considers the factors described in this study is essential to demonstrate to certification agencies that key requirements and regulations have been met. V&V can also be integrated throughout the system development life cycle to ensure that prototypes continue to satisfy the design and requirements.

Figure 24. Offshore wind turbines. (Source: Shutterstock)

The use of V&V after the system has been deployed can enable lessons to be learned in the operation of the system and inform requirements for future systems that have yet to be developed. Furthermore, the ability of the system to meet its design specifications and requirements may be useful to regulators wishing to determine future regulations. For example, a battery system for an autonomous vessel might meet requirements at the point the system is deployed, but it may be found afterwards that the battery degrades quickly, increasing maintenance costs and causing adverse environmental effects during disposal. Therefore, a regulator may wish to specify that a different battery technology should be used in systems developed in future. Note that broader sustainability issues, while not considered in this article, are clearly important to the development and deployment of robotic systems and robotics standards, for example BS8611 (see Appendix), are beginning to highlight this area.

Finally, V&V can be incorporated as part of the autonomous system itself, in a process known as self-certification [51]. Since autonomous systems can be made to be "aware" of their condition after deployment, they can monitor their sub-systems in real-time to determine that they are still meeting requirements and design specifications [52]. This process can also extend to requirements based on regulations, where the autonomous system may determine that any further operation may result in prohibited activity. Autonomous systems capable of self-certification can also alert their operators to the need to perform repairs or upgrades as necessary. Techniques from prognostics and health-monitoring [53] can also be used to make long-term predictions about key issues such as remaining useful life of components or even the system itself, so that operators can anticipate the amount of work that can be done by the system and plan for maintenance and repair in the medium and long term.

"Since autonomous systems can be made to be "aware" of their condition after deployment, they can monitor their sub-systems in real-time to determine that they are still meeting requirements and design specifications."

About the Author Organisations

A. Offshore Renewable Energy (ORE) Catapult

ORE Catapult is the UK's leading technology innovation and research centre for offshore renewable energy. Our strategy is to leverage our unique facilities and expertise to work in close partnership with the heavyweights of the offshore renewables industry – the OEMs and other large industrials, the developers and owner/operators – to improve existing and develop next generation renewable energy technology in the UK. In so doing, we enable and support the development of a vibrant indigenous supply chain, provide a clear route to market for innovative new companies and technologies, and direct and pull through applied research from the UK's world-leading academic base.

ORE Catapult has been involved in a wide range of projects supporting the development of cutting-edge robotics and autonomous systems for the offshore renewable energy industry. Countless companies, and consortiums have supported by ORE Catapult to develop, test, and demonstrate new robotics capability. This has included surface vessels for rapid environmental surveys, climbing robots capable of new non-destructive inspections, drones for blade inspection, underwater vehicles for creating real-time 3D-models of assets, and cooperative robotic systems made up of aerial, surface and underwater vehicles.

B. ORCA Hub

The ORCA Hub is the world's largest robotics and artificial intelligence development consortium for the offshore sector. The multimillion-pound programme is aimed at addressing the offshore energy industry's vision for completely autonomous and semi-autonomous offshore energy production; controlled, inspected, maintained, and repaired from the safety of onshore.

Launched in October 2017, ORCA Hub is part of the UK government's £93m R&D funding of "Robotics and AI for Extreme Environments" through the Industry Strategic Challenge Fund (ISCF). The fund is delivered by UK Research and Innovation and managed by EPSRC.

Led by the Edinburgh Centre for Robotics (Heriot-Watt University and the University of Edinburgh), in collaboration with Imperial College London, University of Liverpool and University of Oxford, the ORCA Hub brings together internationally leading robotics experts with over 30 industry partners to create a multidisciplinary consortium with unique expertise in:

- Mapping, surveying, and inspection,
- Planning, control, and manipulation,
- Human-robot interaction with explainable AI, and
- Robot and asset self-certification

C. Royal IHC

Royal IHC is a supplier of innovative and efficient equipment, vessels, and services for the offshore, dredging, and wet mining markets. Royal IHC enables its customers to execute complex projects from sea level to ocean floor in the most challenging of maritime environments.

With a history steeped in Dutch shipbuilding since the mid-17th Century, Royal IHC have in-depth knowledge and expertise of engineering and manufacturing high performance integrated vessels and equipment and providing sustainable services. From a head office in The Netherlands and with more than 3,000 employees working from sites and offices on a global basis, they are able to ensure a local presence and support on every continent.

Dredging operators, oil and gas corporations, offshore contractors, mining houses and government authorities all over the world benefit from Royal IHC's high quality solutions and services. With a commitment to technological innovation, in which sustainability and safety are key, Royal IHC strive to continuously meet the specific needs of each customer in a rapidly evolving world.

Acknowledgements

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Figure 25 Heriot-Watt University lab-scale AUV testing. (Source: Heriot-Watt University)

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Appendix: Regulations and Standards for Offshore Autonomous Systems

Governments often delegate the control of a distinct economic activity to a specific regulator, who can monitor and supervise that activity and ensure that it remains in the public interest. Regulators produce legislation which must be followed by the organisations and individuals engaged in that activity. There are number of regulators that are directly relevant to the developers of offshore autonomous systems. For example, in the UK these include the Civil Aviation Authority, the Maritime and Coastguard Agency, and Ofcom (e.g., radio licensing). Classification societies like Lloyds Register also produce regulations that must be met before a classification certificate can be given to a vessel or offshore structure. Regulators often provide certification of assets that allows organisations to determine that assets have met the required regulations. Other regulators may provide broader guidance which applies to many sectors, such as the Health and Safety Executive (HSE) in the UK, which regulates safety within the workplace. Certification can also apply to individuals and organisations, e.g., when an external body has determined that they possess a particular capability. Licensing also applies to individuals and organisations and means that a permission has been granted to that person/body.

Additionally, standards are used in the development of complex systems, and often resemble regulations in the way they are presented. However, standards are not legally enforceable (unlike regulations), and instead represent agreed conventions and best practices within an industry. For example, the size of A4 paper is a standard defined by the International Organisation for Standardisation (ISO) in the ISO 216 document. The use of a common standard allows for increases in interoperability and efficiency between organisations.

In practice, regulations, standards, licensing, and certification are all used to ensure the safety and reliability of systems. However, it is important to note that these documents and processes are not synonymous with safety, and that systems developed to regulations and standards may not be safe. Likewise, systems that have not been developed to regulations and standards are not necessarily unsafe.

Whereas autonomous systems present a range of new challenges for engineers, it is important to note that many existing standards for non-autonomous systems will still apply. For example, the applicable regulations and standards will depend on the technologies used by the autonomous system, but in the UK they may include:

- The Merchant Shipping (Vessel Traffic Monitoring and Reporting Requirements) Regulations 2011.
- CAA CAP 393: The Air Navigation Order 2016 and Regulations.
- IEC 61508: Functional Safety of Electrical/Electronic/Programmable Electronic Safety-related Systems.
- RTCA DO-178B/C: Software Considerations in Airborne Systems and Equipment Certification.
- SAE ARP4754 - Guidelines for Development of Civil Aircraft and Systems.
- ISO 26262: Road Vehicles - Functional Safety.
- ISO 10218: Safety Requirements for Industrial Robots.
- ISO 18646: Robotics - Performance criteria and related test methods for service robots.
- ISO 20218: Robotics - Safety design for industrial robot systems.

Figure 26. Offshore substation and wind turbine. (Source: Ramboll)

In addition, there are a number of new and developing documents that apply in particular to autonomous systems:

- Maritime UK: Maritime Autonomous Surface Ships - UK Code of Practice.
- UK Marine Industries Alliance (MIA): Industry Code of Conduct for Maritime Autonomous Systems.
- Lloyds Register - Cyber-Enabled Ships: ShipRight Procedure Assignment for Cyber Descriptive Notes for Autonomous & Remote Access Ships.
- Lloyds Register - Code for Unmanned Marine Systems.
- CAP 722: Unmanned Aircraft System Operations in UK Airspace - Guidance
- BS 8611 - Guide to the Ethical Design and Application of Robots and Robotic Systems.
- IEEE P7001 - Transparency of Autonomous Systems.
- IEEE P7006 - Standard for Personal Data Artificial Intelligence (AI) Agent.
- IEEE P7007 - Ontological Standard for Ethically Driven Robotics and Automation Systems.
- IEEE P7008 - Standard for Ethically Driven Nudging for Robotic, Intelligent and Autonomous Systems.
- IEEE P7009 - Standard for Fail-Safe Design of Autonomous and Semi-Autonomous Systems.
- IEEE P7010 - Well-being Metrics for Autonomous and Intelligent Systems.
- IEEE P7014 - Standard for Ethical considerations in Emulated Empathy in Autonomous and Intelligent Systems.
- ISO 15066: Collaborative robots.

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Figure 27. Offshore wind turbines near shore. (Source: iStock)

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