Net Zero Oceanographic Capability - Scoping Study

WP4: Future Marine Autonomous Systems

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In 2019, UKRI (NERC) commissioned the National Oceanography Centre to identify the options for developing a world-class oceanographic capability with a reduced carbon footprint by presenting a range of options for transitioning to low or zero carbon capabilities. 6 work packages were initiated to examine the science and policy drivers for a future research capability and the various technologies that could enable the capability. The findings of the 6 work packages and a number of independent reports commissioned under the NZOC banner were combined in the NZOC Summary Report that provides more information about the project.

This report covers the detailed findings of Work Package 4: Future Marine Autonomous Systems.

Executive Summary

This report forms part of the broader Net Zero Oceanographic Capabilities (NZOC) project, whose aims are to develop a zero-carbon observing system for the UK's marine science community by 2035. The report focuses on the developments of marine autonomous systems (MAS) and how they can play a role in this transition. It needs to be read alongside the ship, sensor and data ecosystem reports to build a fuller picture of the project.

The report looks at broad trends in the developments of marine robotics and the opportunities and challenges to further support marine science. It leans heavily on the outputs of the marine robotics and sensors NZOC engagement workshop to bring in the broader community context. The report looks in detail at the critical subsystems of energy, communication and autonomy to show how changes in these areas will open up new capabilities. Key challenges are also identified, and science operations that are hard to move to marine robotics, such as heavy infrastructure deployment and sampling, are highlighted. A large portion, but not all, of these challenges, can be overcome in the next 15 years, assuming continued financial investment.

The report also gives a simple review of the carbon cost of using existing marine robots and research vessels. Due to their small size, marine robots use substantially less energy to manufacture and operate than a crewed research vessel; it turns out the power source is far less important than the size difference. Thus, moving measurements from crewed vessels to marine robotics provides a clear route to reducing carbon.

Although marine robotics will provide a critical component to low carbon observing, structural barriers associated with cost and "best practice" protocols need to be overcome. It is likely that marine robotics, although far lower carbon, will initially be more expensive and will provide lower quality data for certain scientific applications. Hence, the science community will not be incentivized to use the systems, which will slow their adoption and slow the transition to low carbon observing. Thus, careful thought should be given to structuring the incentives and choice architecture to drive the adoption of lower carbon observing methods. The drive to transition to low carbon observing should be a consistent thread woven into the fabric of all operations and developments, and we should make it easy and preferable for the science community to choose the low carbon option.

Key Recommendations

1. Although the current marine robots are capable, continued funding is required to develop the fleet to enables the transition to low carbon observing. This would involve enhancing the autonomy & controls systems, integration of new sensors, adding new capabilities, and growing the fleet.
2. Certain measurements are currently made from ships which could be relatively easily made using marine robotics, e.g. upper ocean biogeochemistry, bathymetric surveys, core hydrographic section measurements. Funding is required to make this transition as although the robotic methods are lower carbon; they may initially be lower quality and higher cost. After the initial transition, follow on funding will be needed to optimise the robot-based protocols to reduce the cost and improve the data, thereby reinforcing the transition.
3. The carbon costs for operations are complex, so to reduce the values, it is important to understand what is generating them. Thus, an estimated carbon cost should be created for each deployment and given to the PI alongside the expedition financial cost. These estimates will enable the National Marine Facilities to target development to reduce the carbon costs and will encourage the science community to think about the carbon cost at the application stage.

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1 Introduction

The development and uptake of marine robotics systems is gathering pace. The early exploitation of this technology from 2000 onwards, initially driven by niche applications in defence, Oil and Gas, and marine science, is moving into the mainstream as the technology and supporting infrastructure become more capable. We are seeing a number of different industries which are driving the development and adoption of the technology. These sectors are:

- Defence
- Offshore energy (e.g. oil & gas and offshore renewables)
- Ocean Science & monitoring (e.g. Met Office, Cefas, Defra, etc.)

MAS (Marine Autonomous Systems) is a technology that utilises developments from other domains such as electric vehicles (battery and autonomy), onshore robotics (software development), mobile computing (low power electronics), and the broad computer science work driving autonomy, machine learning, and AI developments. The uptake of MAS would not be possible without these other technology innovations.

Given this reliance on the broader technology landscape, predicting how MAS will develop over the next 15 years is difficult. The funding to develop marine robotics is tiny compared to that used in developing the supporting technology (e.g. mobile computing, computer science, and electric vehicles). Likewise, the funding to develop oceanographic robotics is small compared to that being spent in the defence and commercial sectors. Thus, the oceanographic MAS developments will need to ride the wave of investments into commercial marine robotics and the broader technology landscape and focus investment on addressing the gaps that the broader industry does not address. However, as these gaps tend to be on the leading edge of what is possible, the oceanographic technology development community can provide thought leadership in this sector.

1.1 Review Scope

This review focuses on the oceanographic community's current and expected use of marine robotics over the next 15 years. Although moorings, landers, and other deployed infrastructure form part of the current observing techniques, their developments are not explicitly reviewed here and are only addressed peripherally. Also, we do not explicitly address the science sensors attached to the platforms, as these are being addressed in detail in Work Package 5. However, we attempt to highlight how the sensor and sampling requirements impact the performance of marine robotics.

The review looks at marine robotics from the industrial, defence and scientific sectors and specifically focuses on AUVs, ocean gliders, USVs, Argo floats, and to a lesser extent, ROVs. It builds on the outputs of the NZOC Workshop 4 and attempts to address the issues explicitly raised by the participants. For example, the developments around energy and communication technology are reviewed in detail as these are critical challenges restricting the adoption of marine robotics. The role of autonomy and software infrastructure is considered and draws on the work of other domains in presenting a current and future view of the state of the art. This review needs to be read alongside the NZOC reports on next-generation research vessels (WP3), sensors and sampling (WP5) and the data ecosystem (WP6) to build a complete picture of the different components that will build the next generation low carbon observing system.

1.2 Net Zero Definition

Currently, no operational oceanographic platform can truly be considered to be zero carbon. Although marine robots do not typically use fossil fuels directly, they still have some carbon impact associated with material extraction, manufacture, transportation, use and disposal. This carbon cost is due to the world's reliance on fossil fuels for energy and material processing. Thus, all current economic activity will have some carbon cost associated with it. As the world moves towards renewable energy generation, the carbon cost of each kWh of energy used will reduce. However, the grids of different countries are decarbonising at different rates, so the carbon cost of a given activity will depend on where it takes place. Given the variability and complexity of calculating the carbon impact of a given deployment, this report only addresses the embodied carbon (associated with manufacture), and the variable carbon (associated with the “fuel” used) for generic classes of platforms.

Note the carbon cost associated with the data ecosystem and shoreside control infrastructure is ignored here.

1.3 Scoping Review Requirements

The core objective of this review is to produce guidance on the investment needed to move the marine robotic technology forward so that it can support the coming low carbon ocean observing system. The review starts with a general overview of the current trends in the marine robotics and autonomy space, and it then reviews the present usage of robots within the science community. Existing limitations with the technology are then outlined, and the impact this is having on the marine science community’s uptake of the systems is discussed. The review then scans the technology trends over the next decade and a half, focusing on specific component technologies. These include energy, communication and autonomy, as these are undergoing significant change and are core enablers of marine robotics. Gaps in the development trends are also identified, and those specific to the marine science domain are highlighted. The carbon cost of both ship-based and marine robotics observations is then estimated. These simple estimates only focus on the embodied carbon and variable fuel costs. The review concludes with a development roadmap for marine robotics to build towards a net-zero oceanographic capability.

2 Baseline Review 2021

2.1 Broad trends in marine autonomous systems

The marine autonomous systems market is developing rapidly. Over the last few years, there has been a significant increase in investment in the offshore energy, ocean science and defence sectors that has been driven by the need to reduce costs, improve data quality, and add new capabilities. These drivers are not expected to decrease, and so it is likely that the market will continue to grow and the technology development will continue to advance rapidly. Within this context several trends are visible.

One of these trends is the removal of people from sea-going roles with a push for autonomy to undertake the dull, dirty and dangerous roles. This is driven from a cost and a safety perspective. As an example, Fugro, a large established marine geotechnical services and data company, is looking to move a significant portion of its staff onshore. Fugro's view is that if your job is to look at a computer screen, you don't need to do this at sea[1]. To that end, they have set up shore-based ROV control centres in different time zones to allow remote pilots to provide 24 hour operations anywhere in the world while still working normal office hours. They are also investing in remotely piloted uncrewed surface vessels to complement their crewed survey fleet.

Newer entrants to the subsea market such as Ocean Infinity, a marine robotics and data company, with their Armada fleet are going one step further. They are moving to full remote fleet operations using shore-side control centres to control uncrewed surface vessels equipped with ROVs and sensor suites. This fully remote approach also allows for fully distributed operations of teams. For example, XOcean, a new marine data collection company utilising remotely piloted USVs, undertook a fully remote multibeam survey with their USV pilots based in Ireland, the vehicle being launched in Norway, and the surveyor analysing the data being based in the UK with none of the team physically meeting[2]. This trend to move people onshore and work as distributed teams has been accelerated by the Covid pandemic as it has restricted people's movement and forced people to work in a remote and distributed way. It is expected that this trend will continue due to the long-term cost savings associated with the approach.

A further trend being seen in the commercial sector is the move towards the data as a service model. Here system developers such as XOcean do not sell their uncrewed surface vessels. Instead, they operate their USVs and sell the data collected. Saildrone, another USV operator, is using a similar business model but for longer range ocean-going USVs. Likewise, Terradepth, a new marine data start-up, is using the same approach for AUVs.

This business model has several advantages for both the developer and the customer compared to selling the vehicles. First, from a developer's perspective, it removes any need for customer training and support. Second, it enables the developer to rapidly improve the platform capabilities as they have first-hand feedback on any operational issues. Finally, from a customer's perspective, the data delivery risk is reduced as the developer carries most of the operational risk. Thus, we are seeing many new entrants using this data as a service model. These new entrants are driving the pace of technology development and pushing the adoption of these disruptive systems. This trend is

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[1] Society of Underwater Technology - Underwater Technology Podcast 29 – Alastair McKie, Fugro, on transition towards remote offshore operations. - https://www.sut.org/publications/the-underwater-technology-podcast/

[2] Society of Underwater Technology - Underwater Technology Podcast 61 – James Ives, CEO XOcean, using uncrewed surface vessels to deliver ocean data - https://www.sut.org/publications/the-underwater-technology-podcast/

accelerating the move from traditional ship-based survey methods to remotely operated and autonomous systems.

Alongside changes in business models we are also seeing increased investment in Autonomous Underwater Vehicles (AUVs), which is leading to a diversification in vehicle types. This diversification occurs as AUVs are being designed to fulfil different operational roles. An example of the range of vehicle sizes is shown in Figure 1, which shows the Boeing Echo Voyager a 26m long extra-large uncrewed underwater vehicle (XLUUV) and an ecoSUB, a 1m long micro AUV.

Figure 1. Left Boeing's Echo Voyager the basis for the US Navy XLUUVs. Right Planet Ocean's ecoSUB micro AUV.

The small (man-portable) market has continued to grow, the low logistical overhead of these systems makes them an appealing option for near coast shallow water surveys. An emerging trend has been the use of multiple small AUVs as autonomous seismic nodes, with systems under development by Autonomous Robotics Ltd and Blue Ocean Seismic Services, amongst others. To date, none of these systems has been deployed at scale.

In the commercial larger scale deep diving AUV market, there has been a recent explosion in vehicles with longstanding offerings from Kongsberg Hugin, ISE Explorer, Hydroid Remus and General Dynamics Blue Fin, being joined by new offerings from Lockheed Martin MARLIN, Kawasaki SPICE, Oceaneering Freedom ROV, Thales ASEMAR, ECA, and Dive. With a further offering on the near horizon from Kraken Robotics. Teledyne Gavia has also recently supplemented its Gavia offering with a 6000m rated Sea Raptor AUV. Kongsberg Hugin has also updated its offering with the addition of Hugin Superior and Hugin Endurance.

The new Hugin Superior, Gavia Sea Raptor, Dive LD, ASEMAR and ECA ALISTAR have all opted for flight style AUVs with a broad survey application, focusing their offering on improved range, and better sensor integration. Other suppliers, such as Oceaneering with their Freedom hybrid AUV / ROV, have targeted the commercial subsea infrastructure survey and inspection market. The Freedom ROV is an untethered vehicle that can operate either as an AUV or ROV (using a through-water high bandwidth communication system) and can be recharged from a subsea dock. Likewise, Subsea 7's Autonomous Inspection Vehicle (AIV), initially trialled in 2010, is another field resident system that uses a garage for recharging and data upload. Alongside the Freedom ROV and the AIV, there are many new entrants into this area. For example, Houston Mechatronics, inc are promoting their Aquanaut vehicle. This experimental vehicle is a transformer system that can efficiently transit to a worksite before transforming to undertake intervention tasks. Another example is Kongsberg's Eelume vehicle which is also designed as a field resident system that can swim around the complex subsea infrastructure in a snake-like motion. This snake-like vehicle is a novel concept and has significant advantages over the existing more compact designs. Although these systems offer the potential for cost savings, it is likely to be several years before there is substantial commercial uptake of field resident AUVs.

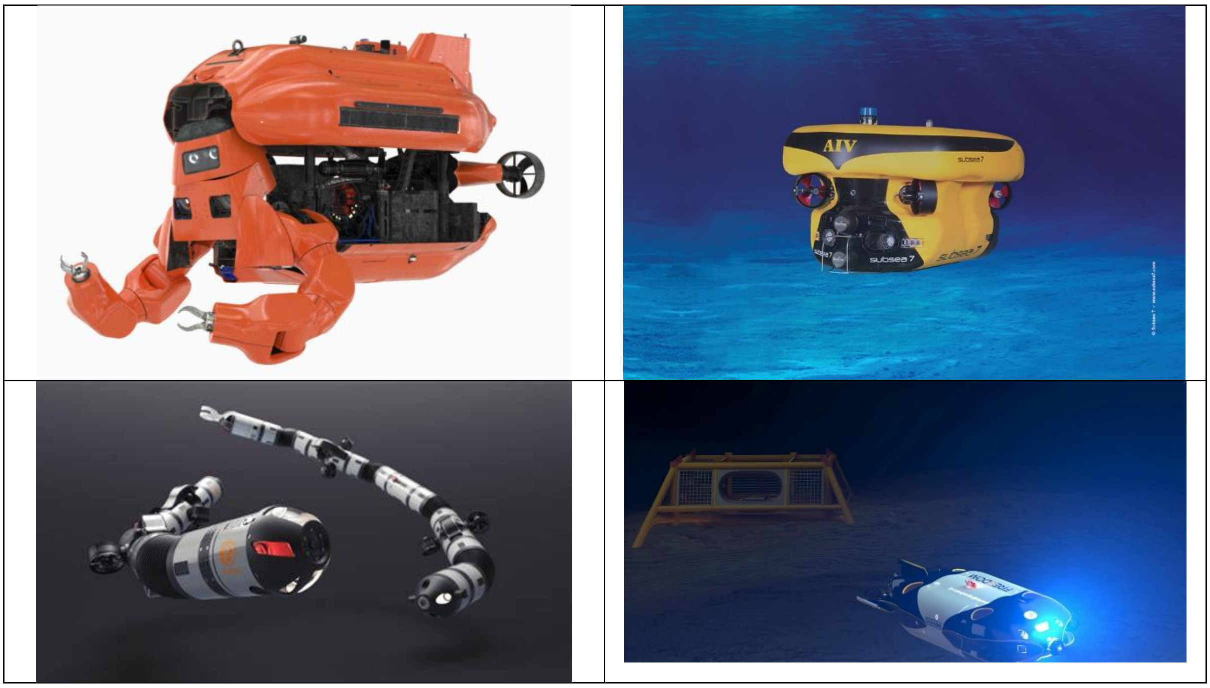

Figure 2. Inspection and Intervention AUVs. Top left Houston Mechatronic inc, Aquanaut; top right Subsea 7's Autonomous Inspection vehicle; and bottom left Kongsbergs's Eelume AUV; bottom right Rendering of Oceaneerings Freedom Hybrid AUV/ROV in action

Alongside field resident systems, there is a drive to develop long-range AUVs; examples include MBARI's Tethys, NOC's Autosub Long Ranges, Kongsbergs's Hugin Endurance and Cellula Robotics Solus LR. These systems are designed to lower operational costs by reducing the need for expensive ship time. These platforms can be launched from shore and then transit under their own energy to the area of operation. The long-range of these platforms also facilitates previously unachievable long-distance transects under ice. Reliability is a critical challenge in this operational model, as lack of vessel support means the systems are required to operate continuously for long periods without local intervention or support.

The navies of the world are also investing heavily in AUV technology. The US is leading this area with a significant investment in a range of AUVs as outlined in the Navy Large Unmanned Surface and Undersea Vehicles: Background and Issues for Congress Report. The UK's Royal Navy is also investing heavily in this area with initial developments of an XLUUV demonstrator being undertaken by MSUB Ltd[3]. The increased tension between the West and Russia means that the subsea domain will likely become a more actively contested area. Autonomous and remote technologies are going to be critical to operating in this arena effectively. Thus, the likes of the Royal Navy are looking to increase their capability in this area rapidly. However, unlike the commercial sector, they are more focused on covert operations and hence more interested in sub-surface vehicles.

We are also seeing a growing trend where multiple platforms are working together as a system of systems to enable more complex data gathering. These teams can be a homogeneous set of vehicles all acting together to form a measurement network, an example being the autonomous ocean bottom seismometers mentioned previously. Alternatively, the vehicles can create a heterogeneous

[3] See https://ukdefencejournal.org.uk/royal-navy-awards-contract-for-large-autonomous-submarine/

team where different vehicles undertake different functions. A reasonably well-developed example of this is to use the USV as a data relay between shore and subsurface systems e.g. instrument suites, or subsurface vehicles. Here, the USV can harvest data from subsurface systems or provide control and navigational aiding to subsurface vehicles. This concept has been technically demonstrated several times and is starting to be actively used. For example, WHOI will use Wave Gliders as a data gateway for their Sentry AUV[4]; MBARI are using Wave Gliders as a communication hotspot[5] to enable communication to their AUVs. NOC has also tested this as part of the NERC ACSIS project. This project evaluated the use of a Wave Glider to acoustically harvest data from the RAPID mooring array.

Taking this one step further, USVs are also being developed and demonstrated, which can launch and, in some circumstances, recover AUVs. Examples of this are the SeaKit USV which can launch and recover a Hugin AUV, and the Autonaut 5m USV being used to launch a Seaglider. This development enables the AUV to be transported to and from the operational area and potentially recharged on-site. As AUVs are energy limited, this is a significant advantage.

A slight variation of this approach is to use the USV to launch and recover an ROV, as demonstrated by the ECA Group[6] with their INSPECTOR USV & H300V ROV configured for subsea inspection maintenance and repair. This combination of USV and ROV is likely to become highly popular due to the potential cost savings involved and is central to the Ocean Infinity Armada concept mentioned previously. This concept is becoming practical because of the improvements in satellite communications (see section **Error! Reference source not found.**).

These are just a few use cases where several vehicles collaborate as part of a measurement network. This linking of platforms into a system of systems will likely become the default operational model, and single systems working alone will become less common.

The trend to move towards remotely operated and autonomous systems is primarily driven by cost reduction and competitiveness for commercial operators. However, as marine robots are generally far smaller than their crewed counterparts, there is a significant reduction in the energy used during operations and in manufacture. Hence, their operational and embodied carbon footprint is lower, aligning with the companies' carbon reduction priorities. Companies are looking to further reduce their carbon footprint by utilising renewable and non-fossil-based fuels to power the marine robots. This has the potential to further reduce the CO_2 emitted.

2.2 Autonomy and Data Management

Until early 2000, most unmanned marine vehicles were tethered and remotely operated. Extensive use of manned submersibles and ROVs were limited to a few applications because of very high operational costs, operator fatigue, and safety issues (Yuh, 2000). Autonomy was interpreted as programming the vehicles to visit scripted, sequential waypoints and equipping them with an operator-designed finite state machine for handling faults by allowing the vehicle to abort or jump to predefined positions in the mission script. Standard capabilities achieved include keeping the vehicle stationary and the velocity constant, following a set of predetermined waypoints, and following structures (e.g., pipelines, cables, algae) using target sensors.

[4] See https://www.whoi.edu/news-insights/content/wave-glider-provides-gateway-to-remote-exploration/
[5] See https://www.mbari.org/technology/emerging-current-tools/communications/wave-glider-based-communications-hotspot/
[6] See https://www.ecagroup.com/en/business/eca-group-successfully-demonstrates-usv-rov-interoperability-for-subsea-inspections-for-total-and-technipfmc

In the past fifteen years, however, the growing commercial demand for advanced marine robot technologies has led to an intense effort in developing autonomous, specialised, reliable robotic vehicles. The research community has focused on increasing the autonomy of the vehicles and minimising the need for the presence of human operators. These developments have been made possible by the rise of new electronics and computing devices, which has allowed for more compact, powerful, and efficient computing resources to be present on board of robotic vehicles and better and more advanced instrumentation.

The commercial push behind the development of autonomous and intelligent marine systems is determined by their usefulness in many different applications. They are increasingly used to map or monitor changes in remote ecosystems, challenged by pollution, global warming, ocean acidification, and invasive species (Yanwu Zhang et al., 2012). They also assist industrial activities such as oil & gas and offshore energy production, including platform and pipeline inspection and subsea installations (Mai et al., 2016). In addition, marine robots are widely used in the defence sector and maritime search and rescue. Adding manipulation capabilities to AUV platforms has led to significant opportunities for close-up observations, sampling, and infrastructure maintenance that were previously only possible with ship supported ROVs (Johansson et al., 2010).

Three main challenges impact the implementation of autonomy for marine robotics. The first challenge is the very nature of the marine environment, which is primarily unknown, unstructured, and dynamic. High Spatio-temporal variability and partial observability are crucial factors to be considered in any solution for autonomy. In addition, the environment imposes limitations in communication with marine robots suffering from bandwidth restrictions, particularly in underwater communication, which often uses acoustic modem transmissions. The environment challenge calls for sophisticated autonomy solutions that include risk identification and minimisation, persistent operations and adaptivity.

The second challenge is linked to the fact that solo missions in marine applications have exhibited drawbacks in terms of mission scope, as single platforms are usually limited in their capabilities, and in terms of mission robustness, as there cannot be any redundancy when using one robot only. The use of a fleet of robots mitigates both these problems but introduces considerable complexity. Multi-robot coordination and collaboration is still a challenging area of research, and an environment that presents partial observability, spatio-temporal variability and limited communication exacerbates such difficulties. Planning/replanning, task decomposition and task allocation are needed to deal with them.

The last challenge relates to the involvement of human operators in (semi-)autonomous missions. As sea operations are hazardous in nature, missions always involve one or more operators who supervise the robotic assets at a distance. Traditionally, the role of human operators has been crucial in relation to task decomposition and allocation, monitoring, risk assessment and contingent replanning. With the rise of fully autonomous operations, the role of the operators is changing, but it remains essential in supervising the mission and ensuring its success. Hence, important challenges are linked to the implementation of shared autonomy, with the vehicle being able to exhibit transparent and reliable behaviours.

Since 2007, when the Monterey Bay Aquarium Research Institute developed the Teleo-Reactive Executive (T-REX) planner (Mcgann et al., 2007) to underpin the control of AUVs, several projects have tried to go beyond scripted behaviours for marine robots to achieve higher levels of autonomy. The use of AI planning technology has become prevalent both in solo and multi-vehicle missions, and the community has focused on overcoming the challenges outlined above. In what follows, we describe some representative developments in this space. We refer the readers to comprehensive reviews for a complete picture of state of the art.

The EU-funded PANDORA project (Maurelli et al., 2016) has targeted persistent autonomy. It has successfully operated AUVs for extended periods (12-48 hours) without the continual presence of a surface vessel in tasks such as structure inspection, valve turning and chain cleaning. A ROS-based architecture is used to integrate all the components of PANDORA. At the top level, an automated planning system (POPF (Coles et al., 2010)) builds a mission plan to achieve a set of inspection and maintenance goals. POPF is a planning system that works with a symbolic representation of the world (PDDL model (Fox & Long, 2003)). The structure of the mission plan is used to coordinate the behaviour of the AUV over a long period of time. The mission plan contains several inter-dependent tactical plans planned in detail by POPF when the mission plan execution reaches them. All planned activities are executed through a ROS architecture that integrates planning with ROS. When a plan fails, it is terminated, the PDDL model is updated, and a new plan is formulated and executed. PANDORA integrates planning with learning by demonstration for performing valve turning and an ontological knowledge base for coping with faults. The scientific results of the project have been field validated in the context of three scenarios, using vehicles available at Heriot-Watt University and Universitat de Girona.

Persistent underwater autonomy is currently an active area of research, and recent work has been focusing on extending autonomous operations from hours to days and weeks. The main obstacle to long-term missions is dealing with the uncertainty of an ever-changing environment. Marine robots need to deal with high variability across large-scale spatiotemporal dimensions while reacting to a locally dynamic and uncertain environment. There are three primary sources of uncertainty, motion, sensing and environmental uncertainty, and handling them underwater is particularly challenging given the limited energy budget of the vehicles and error-prone underwater sensor measurements and navigation. To face these challenges, planning for long-term AUV autonomy under uncertainties is usually framed as a decision-theoretic problem. Recently, Newaz et al. (RedwanNewaz et al., 2021) have proposed an Energy Cost-Constrained Partially Observable Monte-Carlo Planner (ECC-POMCP) for solving an Energy Cost-Constrained Partially Observable Markov Decision Process (ECC-POMDP) problem in a continuous state space representing a marine environment under motion, sensing, and environment uncertainties. The ECC-POMCP optimises the trade-off among the rewards, the energy costs, and the collision costs. The planner works in tandem with a recurrent neural network (RNN) based learning algorithm, which predicts ocean dynamics from real ocean current data in a continuous domain. The effectiveness of the ECC-POMCP algorithm has been validated via simulation and real-world experiments conducted off the coast of North Beach, Miami Beach, FL, USA.

Another area of intense research has been risk-aware planning. Operations of AUVs in coastal regions, as opposed to deep water, expose AUVs to the risk of collision with ships and land. As discussed above, such concerns are exacerbated by the uncertainty in the ocean current predictions, which can lead to significant alterations of planned paths. Pereira et al. (Pereira et al., 2013) propose two stochastic planners that utilise ocean current predictions in a probabilistic manner. Both planners revolve around the notion of minimising the expected risk of collision, which helps them handle uncertainty in ocean current predictions as well as navigational uncertainty in their respective planning frameworks. They exploit a risk map constructed based on historical Automatic Identification System (AIS) data. Points in the map give the likelihood of the AUV surfacing in a location where there is a known shipping hazard. The Minimum Expected Risk planner finds shortest paths in the map that minimise the cumulative surfacing risk for the AUV. The Risk-Averse Markov Decision Process (MDP) planner, on the other hand, utilises probabilistic action models based upon ocean predictions. Field trials indicated the practical effectiveness of both techniques over long-term deployments.

The applicability of the planners such as those proposed by Pereira et al. is limited to cases in which high fidelity ocean models are available. To overcome this limitation, Hollinger et al. (Hollinger et al., 2016) propose using Gaussian processes (GPs) augmented with interpolation variance to provide confidence measures on predictions. They put forward two planners that incorporate these confidence measures: a Stationary Risk-Aware GPMDP (for low-variability currents), and a Nonstationary Risk-Aware NS-GPMDP (for faster and high-variability currents). Extensive simulations and field trials show that the learned confidence measures allow for safe and reliable operation with uncertain ocean current models.

Timmons et al. (Timmons et al., 2019) propose a risk-bounded, goal-directed planning system for ocean exploration mission planning with AUV gliders. Two main risk-aware planning components are coordinated to address uncertainty in the decision/activity and locomotion levels: an activity planning component and a path planning component. The risk-aware planning component consists of a risk-sensitive activity planner that accounts for temporal disturbances while generating plans that satisfy the user-specified mission goals and constraints on operational risk. The current planner incorporates probabilistic models of activity delay, which it employs within a risk-aware temporal consistency checker to allow the planner to evaluate the uncertainty in action duration explicitly. The risk-aware path planning component uses a mixed-integer linear programming (MILP) planner specialised for glider motion that allows a vehicle to traverse an environment with bounded risk on obstacle collision and goal satisfaction. The two components are integrated to allow the unification of the activity and path planning processes, in which the activity planner employs the path planner to check and compute safe paths for vehicle traversal actions. Deployments of the planning system in the Santa Barbara Basin and Cape Cod Bay showed the effectiveness of this approach.

Ocean exploration can be formulated as adaptive sampling, i.e. as the identification and confirmation of high reward regions via repeated measurements. For example, underwater robots may be tasked with locating areas with high temperatures, algal and plankton blooms, or high concentrations of pollutants. As these missions are performed because the environment is not well understood, they require adaptive planners capable of updating plans based on new measurements. At the same time, disturbances and noises need to be handled to make the exploration safe. There is, therefore, a trade-off between allowed risk and expected reward over which the autonomous system should be able to reason. Ayton et al. (Ayton et al., 2019) propose a method of planning an adaptive policy that maximises the expected reward of samples while limiting the probability of failure of the policy. They define a technique of specifying tolerance for failure as a function of reward through a risk bounding function and enforce the constraint that the expected rate of failure is bounded by the risk-bounding function applied to the expected reward. The method is based on Monte Carlo Tree Search, which allows a solution to be found in an anytime manner, making it suitable for onboard autonomy and missions with tight time constraints.

The use of a fleet of heterogeneous autonomous marine robots, including AUVs, autonomous surface vehicles (ASVs), buoyancy-driven gliders and unmanned aerial vehicles (UAVs), is another research area that has recently attracted significant interest (Thompson & Guihen, 2019). Fleets allow for parallelisation of missions, intervehicle support for longer deployment times, adaptability to in situ mission changes, and effective use of vehicles based on their specificities.

As an example, in 2016, the Norwegian University of Science and Technology, the Norwegian Defence Research Establishment, Kongsberg Seatex AS, Radionor Communication AS, Maritime Robotics AS and the Laboratório de Sistemas e Tecnologias Subaquáticas (LSTS), University of Porto set up a comprehensive experiment to explore their capability to combine heterogeneous vessels, including AUVs, ASVs and UAVs, in a network of unmanned vehicles for seabed mapping and target identification (Ludvigsen et al., 2016). An MBR (Maritime Broadband Radios) broadband radio system was implemented to provide communication between the vehicles, and the LSTS software toolchain was used for controlling them (Ferreira et al., 2017). The LSTS toolchain offers different control layers, from plan-level to manoeuvre-level to guidance-level control. The plan-level and manoeuvre-level control can be done onboard the vehicle (fully autonomous operation) or can be controlled by an external operator console while the vehicle is within communication reach. The experiment made it apparent that networks of heterogenous assets have the potential of significantly saving costs for data collection in marine research and management by reducing ship time. In addition, several vital capabilities were demonstrated, such as formation manoeuvring, onboard data processing and target recognition, communication for retrieval of data sets, vehicle re-direction and data relaying within the network. At the same time, the experiment showed that direct communication with a human operator was required to produce effective coordination between aerial, surface, and submerged resources. Subsequently, a mixed-initiative planner called EUROPtus (Py et al., 2017) was integrated into the LSTS toolchain to control a fleet of AUVs and UAVs to perform cetacean monitoring. The centralised, deliberative planner can decompose abstract operator tasks and schedule them to nominated vehicles, allowing the operator to focus on risk analysis and sampling strategies for each vehicle.

Recent work on multi-agent systems for marine applications has focused on interoperability between different vehicles (Costanzi et al., 2018), producing practical algorithms for integrated task decomposition and allocation (Carreno et al., 2020), and robust architecture that breaks the typical boundaries between the autonomy and the communications stacks (Hamilton et al., 2020).

2.3 Current Science Capabilities of Marine Robotics

The capabilities of marine robots are increasing rapidly, and although the types of data they can gather is growing, it is still a small subset of data collected by the marine science community. This was evident from the discussions during the NZOC Workshop 4 breakouts. The types of data collected by marine robots and related systems are discussed below.

2.3.1 Argo Floats

The global Argo programme[7] has had a significant impact on our ability to understand the world's oceans. The programme has been running for 20 years and currently has 3880 floats distributed globally as of August 2021. These floats typically profile to 2000m and collect temperature and salinity data. The data is then sent back over the Argos satellite network. Once received by the ground stations, the float data is quality checked, aggregated by the Argo Global Data Assembly Centres (GDACs) and ingested into climate forecast models in near real-time.

The floats need to be well distributed through the world's oceans to maximise the Argo array's data value. This even distribution is maintained by deploying new floats in areas of low float density using vessels of opportunity. This is possible because the floats are configured to be simple to launch by anyone. However, maintaining the float density in areas with little ship traffic can be challenging (e.g. the Southern Ocean), and thus the deployment programme relies on Research Ships in these areas. Finally, given the low cost of the floats and the difficulty recovering them, they are typically left in the sea.

[7] See https://argo.ucsd.edu/

The classic Argo floats are equipped with temperature, conductivity, and pressure sensors to provide information on ocean physics. These classic floats are being augmented under the biogeochemical (BGC) Argo[8] initiative to measure other Essential Ocean Variables and Essential Carbon Variables. This is achieved by the addition of extra sensors onto the BGC Argo floats (e.g. Oxygen, Nitrate, pH, etc.). Alongside the BGC Argo programme, other floats are being used with increased operational depth as part of the Deep Argo programme[9]. These deep floats extend the profiles down to 6000m. The BGC and Deep Argo float usage will further enhance the value of the data collected by the global Argo array.

At first glance, the Argo array appears to provide an extremely low carbon impact measurement capability. The floats, once deployed, have a tiny carbon cost per measurement as they typically last five years on one battery pack, but they rely on carbon-intensive ships to be deployed. Alongside the deployment, the float data is quality checked against ship-based hydrographic sections (e.g. GO-SHIP) to assess the Argo pressure and salinity bias (Wong et al, 2020). Thus, although the Argo array is very low carbon, it heavily relies on the carbon-intensive research vessel fleet, and a significant reduction in this fleet could jeopardise the array capabilities.

2.3.2 Gliders & long range AUVs

The ocean glider concept was originally described by Henry Stommel in his visionary paper "The Slocum Mission" (Stommel, 1989). Here ocean gliders would travel the oceans being guided via satellite from shore and returning collected data in near real-time using the same satellite link. Subsequent developments made ocean-going gliders a reality, with operational systems being available in the early 2000s (Eriksen et al., 2001; Webb et al., 2001).

Since these early days, the use of ocean gliders has steadily increased within the academic and defence sectors. Their relatively low cost means they are often operated by science teams focused on ocean physics and are becoming an integral part of the Global Ocean Observing System (GOOS) (Testor et al., 2019, 2010). Specific application areas are boundary currents, storms, and water mass transformations as outlined by the GOOS OceanGlider Task Teams[10]. Alongside these applications, gliders are also starting to be used for ocean health monitoring. Here, the vehicles have been equipped with nutrient sensors (Vincent et al., 2018), fluorimeters, and passive acoustic monitoring systems (Davis et al., 2016), amongst others. These science areas are less well established but are growing in popularity.

Gliders have also been used for operations near (Miles et al., 2016) and under ice (Webster et al., 2015) in both the Arctic and Antarctic. Operation in these areas are a high-risk activity and so tend to be limited to only a few highly skilled science users. Often the gliders are treated as either semi or fully disposable, as in the case of the ORBIS project (Dutrieux et al., 2018). There is considerable interest to enhance glider capabilities to enable them to operate under the ice more routinely.

Alongside the under-ice developments, gliders are continuing to be developed (e.g. Teledyne Webbs recent Slocum G3 release) and refined with the addition of new sensors (e.g. the RBR Legato CTD) and operating capabilities (e.g. Teledyne rechargeable batteries). One area of development is the push to increase the glider depth rating to 6000m, with the University of Washington's Deepglider (Osse, 2007) and the H2020 BRIDGES project (Buisson, 2019) being notable examples. However, the

[8] See https://biogeochemical-argo.org/
[9] See https://argo.ucsd.edu/expansion/deep-argo-mission/
[10] See https://www.oceangliders.org/taskteams/

limited commercial interest in deep rated gliders has meant that there are currently no commercially available systems.

Gliders are often launched & recovered from shore by small boats. This means that they are not always reliant on large global class research vessels for their operations. Shore launching and the gliders small size means that they have a tiny carbon footprint, with the leading carbon costs being the primary battery used to power the vehicle.

Complementing glider operations are the new long-range AUVs described earlier (e.g. MBARI's Tethys and NOC's Autosub Long Range – see Figure 3). These platforms offer a similar range to gliders but can carry increased sensor payloads at higher speeds. Thus, they have a more comprehensive range of applications from Ocean Physics, through nutrient and carbonate system measurements, to seafloor mapping (either optically or acoustically). However, this increased range comes at the expense of a larger platform that is less easy to launch and recover and increases operating costs. The larger size also increases the carbon footprint of these vehicles compared to the smaller gliders.

Figure 3 NOC's Autosub Long Range AUVs. ALR1500 foreground and ALR600 in the background

2.3.3 Uncrewed surface vessels supporting science

USVs are being regularly used for bathymetric surveys both on and off the continental shelf. XOcean, mentioned previously, are focused on high-resolution shallow water surveys using a high-frequency multibeam sonar fitted to their USV. Whereas the Saildrone voyager USV is equipped with a low-frequency deep ocean multibeam and is focused on mapping the abyssal planes to produce data for the likes of the Nippon Foundation - GEBCO Seabed 2030 project. High-resolution surveys in the deep ocean are not possible from the surface due to the attenuation in water of high-frequency sound. However, this limitation can be overcome by pairing a USV mother ship with a deep diving AUV equipped with a high-frequency multibeam sonar. An example of this pairing is the Sea-Kit USV and Hugin AUV, which won the Shell Ocean Discovery XPrize.

Along with bathymetric surveys, USVs are being used to measure gas fluxes across the air-sea interface with a particular emphasis on measuring CO_2. These measurements are typically done using long-range lower power USVs. The Wave Glider platform has been used to measure CO_2 fluxes, with the NOAA-PMEL Carbon Wave Glider (Willcox et al., 2009) and the MBARI Wave Glider (Chavez et al., 2018) being examples. More recently, NOAA and Saildrone (Sutton et al., 2021) undertook a complete circumnavigation of Antarctica, measuring CO_2 fluxes during the winter of 2019 using a specially modified Saildrone vehicle. This vehicle was deployed for 196 days and covered more than 13,000 miles. It provided critical information about carbon exchange in the Southern Ocean, a massively under-sampled area of the planet.

USVs have also been used to measure meteorological parameters (Thomson & Girton, 2017). However, for some of the smaller lower-lying vehicles, the sensor data quality was reported to be poor by some of the NZOC Workshop 4 participants. For larger vehicles, it is expected that this is less likely to be a problem.

Smaller long-range USVs are also being used for ocean noise measurements using towed passive acoustic arrays. This is still very much in the demonstrator phase with different sectors exploring different use cases. For example, the military are focused on anti-submarine warfare (ASW) research, as demonstrated by NATO's Centre of Maritime Research and Experimentation (CMRE) and their Dynamic Manta exercise. In contrast, the offshore energy sector is looking at anthropogenic noise associated with their activities. An example of this is the Autonaut case study[11] describing noise measurements around a Mobile Offshore Drilling Unit.

USVs are also ideal platforms to harvest data from subsurface instruments, and to provide a data gateway and navigational aid to subsurface vehicles such as AUVs. This concept has been technically demonstrated a number of times and is starting to be actively used. For example, WHOI will use a Wave Gliders as a data gateway for their Sentry vehicle[12], and MBARI are using one of their Wave Gliders as a communication hotspot to enable communication to their AUVs subsurface. Finally, NOC has also tested the data harvesting concept as part of the NERC ACSIS project. This project was focused on evaluating the use of a Wave Glider to acoustically harvest data from the RAPID array.

The carbon costs of using USVs varies considerably with size, the smaller systems powered from renewable sources are extremely environmentally friendly with very low CO_2 emissions. However, as vehicles get larger and move to diesel-powered systems, the benefits reduce. Also, although USVs are very environmentally friendly, they do not measure anything below the surface, most of which can be more effectively covered by satellite on a global scale.

2.3.4 Oceanographic ROVs & Large AUVs – Current Science Capabilities

The research community has used high powered short-range shipborne AUVs and ROVs extensively over the last two decades. The AUVs and ROVs operate at complementary length scales to research ships. While ships provide large area surveys, AUVs are optimal at a medium scale, and ROVs are excellent at a fine scale. Thus, ships, AUVs and ROVs are often used together to perform nested scale surveys. ROVs and AUVs range in size from very small to very large. Broadly larger systems are needed for deeper water, with vehicles under 100kg being able to operate to a few hundred meters and vehicles needing to be several tonnes to get to 6000m. This relationship is true for both AUVs and ROVs, but with ROVs typically being heavier.

[11] See http://www.autonautusv.com/sites/default/files/Noise%20Measurement%20Case%20Study.pdf
[12] See https://www.whoi.edu/news-insights/content/wave-glider-provides-gateway-to-remote-exploration/

ROVs are used extensively where close up inspection and intervention with the seabed is necessary. They excel at biological sampling and detailed visual inspection. They can also take geological samples with limited push core and drop stone collection. They can also perform fine-scale surveys using high-frequency acoustics, laser scanners, or camera systems. The pilot in the loop controlling operations makes them highly flexible, so it is simple to adapt an ROV to transport and run an experiment on the seabed. Their adaptability also makes them excellent at locating and recovering lost instrumentation or platforms. The primary disadvantages of deep-water ROVs are their size (both for the vehicle and the supporting infrastructure), the number of staff needed to run them, and the power required to drive them.

The large AUVs are primarily used for acoustic and wide area optical surveys of the deep ocean. They are typically equipped with Multibeam and sidescan sonars, sub-bottom profilers, and camera systems. They also carry CTDs, and downward-facing ADCPs for physical oceanographic measurements, but these are typically of secondary importance. Given the nature of the platforms as sensor taxis, they are routinely modified to take bespoke mission-specific sensors for different science campaigns. Examples of this include the integration of flow cytometers, eDNA sensors, eH sensors, etc. Larger AUVs have also been used for under-ice surveys. This is a high-risk activity so it tends to be limited to operations for science users. AUVs are the only system that can be used for this sort of activity.

Due to the size of these deep-water systems, they must be operated from large crewed research vessels, and hence although they may be relatively low carbon, the research ships they operate from typically aren't. As noted previously, USVs are being developed to launch and recover ROVs and AUVs, which would reduce the carbon impact. However, as the deep ocean science AUVs and ROVs are either bespoke or highly modified commercial systems, they may not be able to utilise these developments without considerable modification.

2.4 Current Science Limitations of Marine Robotics

A large amount of the data needed by the marine science community cannot currently be collected using Marine Robots. Thus, without increasing the capabilities of marine robots and their associated sensors, any reduction in research ship availability will curtail the community's ability to undertake ocean science. The key limitations in MAS capabilities were highlighted in workshop 4 of the NZOC project and are discussed below.

The current endurance and range of marine robots were considered an issue by the workshop participants. The problem is marine robots, excluding USVs that harvest energy from the environment, need to carry all the energy required for the mission. Thus, to go further, you need to either increase the available onboard energy, reduce the energy requirement, or arrange to recharge the vehicle mid-mission. The energy can be increased by using a higher energy density power source or by increasing the space available to the energy payload. The energy requirements can be reduced by using lower power electronics and sensors or going slowly. Unfortunately, none of the technical approaches is easy to implement, and so the platforms are only improving incrementally.

The result of the limited onboard energy is that it can be challenging to get the vehicle to the target science location in a timely manner (or at all) if a deployment vessel is not used. The limited energy also restricts the types of sensors fitted to the marine robots, as sensor payload power over a 10W or so will severely limit the vehicle range. Thus, for example multibeam sonars could not be routinely used. Similarly, this prevents very power-hungry infrastructure (e.g. Rock Drills, Seismics suites, and ROVs) being run autonomously. Given the outlined issues, the concern was that without a research vessel in support, a large portion of the world's oceans would be inaccessible to measure even for the currently limited set of sensors available to marine robots.

Although a given sensor can be fitted to a marine robot, it does not mean the sensor will produce good data. Firstly, the platform and sensor will interact, which can degrade the value of the sensor data (e.g. using a passive acoustic monitoring system on a loud AUV). Secondly, the robot may not be able to perform the necessary manoeuvre to take the measurement, e.g. remaining stationary, or getting close to the underside of an ice sheet. Thirdly, the robot may not be able to accurately position itself relative to some geographic reference frame. This inaccuracy is likely to occur when midwater with no surface or subsurface aiding. Some of these issues will be resolved by improving the vehicle's ability to manoeuvre in complex terrain by enhancing its onboard autonomy. Precise AUV positioning can be achieved with some form of aiding external to the AUV, for example, by pairing the vehicle with a USV to provide the navigational aiding. Although these issues are being reduced by new developments, the current MAS capabilities do not provide the same performance as that achieved using current ship-based methods.

Also, the current long-range vehicle to shore communication is via satellite; this has limited bandwidth and is expensive. It also means only a limited amount of data can be sent back during the mission, with the complete data set being stored onboard. This inability to send back the full dataset means that if the vehicle is lost, you lose most of the data. It also means there is a finite amount of data storage available on the vehicle. This could become an issue for long endurance missions using high data rate sensors. Also, only sending back a subset of data means that it is hard to build a clear operational picture to use to effectively retask the robot. A partial solution to resolve both problems is to process the raw data on the vehicle, using the edge computing concept, and then send back the critical information to shore. This would allow valuable information to be collected, even if the vehicle is lost, and enable better operational decisions to be made. The development of the vehicle's edge computing capability and the associated sensor processing algorithms would need to be coupled with the command and control and data ecosystem development to provide maximum impact.

There was considerable concern over the reliability of the vehicles and what would happen if there was an issue mid-mission. Would the vehicle be rescued? Would it be abandoned? Would all the data be lost? As the mission lengths increase, so will the chance of loss as there will be no one to undertake any preventative maintenance, as is currently done using the higher power AUVs and ROVs.

The broad view from NZOC Workshop 4 was that the current sensors available on the MAS could not make all the measurements needed by the science community. This was either because the sensors were not available for the vehicle (e.g. Mass Spectrometers) or that the performance of the sensors was not good enough (e.g. CTDs for Hydrographic sections). There were also concerns around sensor drift, sensor reliability and biofouling. Alongside the worries around sensor drift, there were related concerns associated with calibration of the sensors and traceability of any standards back to a known reference. The question of whether any onboard standards would drift was also raised. These concerns result in a lack of trust in the quality of the data coming from the marine robot-based sensors. The gold standard was considered to come from lab-based protocols either run at sea or back on land, so moving to marine robot-based measurements would degrade or remove the ability to undertake marine science.

Alongside the limitations of marine robotic sensors, the vehicles are unable to take the majority of the water, biological, and geological samples required by the marine science community. This inability is partly due to the limited intelligence of marine robots to select a target, manoeuvre towards the object, and then collect the sample. However, the main limitations are due to space, power and energy constraints. If these sampling issues can be overcome, the next hurdle will be preserving the sample to prevent degradation between collection and analysis onshore. Currently, one of the primary preservation techniques is to freeze the samples and store them in -80°C freezers. Using a similar technique on a subsurface vehicle is extremely technically challenging. These issues explain why sampling is hardly ever done by marine robots, and to move the technology forward to enable sampling to take place would require a number of significant technological hurdles to be overcome.

An alternative approach would be to analyse the sample in situ instead of returning it to shore for analysis. This may be a simpler approach, but it does mean that the sample won't be available for reanalysis by other scientists; reanalysis onshore would be far lower carbon than collecting another sample. Also, each specific measurand is likely to need bespoke vehicle-based technology to take the measurement, whereas returning with the sample allows the analysis to be done using shore-based equipment.

Alongside the sampling issues, MAS platforms cannot currently launch and recover fixed platforms to the seabed, something that is relatively easy from a crewed ship. The most significant limitation is the deployment and recovery of moorings. The moorings themselves are very low carbon, but, like the Argo floats, they rely on ships for their launch and recovery. Alongside moorings, MAS platforms cannot easily launch and recover landers or other bespoke seabed experiments. Thus, moving to a purely MAS based solution would significantly hamper the opportunity to deploy these sorts of experiments.

3 Horizon Scanning 2020-2035

Marine Autonomous Systems comprise a large, complex, and rapidly changing field. Hence predicting how the systems will develop over the next decade and a half is extremely difficult. However, as noted in section 2.1, we can tease out some broad trends which will address some of the concerns expressed during NZOC workshop 4.

From section 2.1, we know from the commercial sector that there will be a continued drive to move people off of the vessel and back to shore, and there will be a push to operating large remotely piloted uncrewed surface vessels. These will be used for surveying, inspection and intervention of offshore infrastructure and will act as the command vessels for ROV and AUV operations. Aligned with these developments will be the creation of new long-range AUVs and field resident systems. The military will also be pushing to develop under ice operational capabilities. Also, as we move towards a more connected world, these systems will be operated as an integrated observing system, rather than being used in isolation as stand-alone systems. There is also likely to be a diversification of vehicle types as the solution space is explored before a set of optimal classes of platforms is converged upon.

All of these developments will need to overcome the same fundamental challenges seen by operators of marine robots, be they from science, commercial or defence sectors. These are shown in Figure 4 taken from the US Navy Congress report “Navy Large Unmanned Surface and Undersea vehicles: Background and Issues for Congress”[13]. Note how these readily map to the challenges raised during the NZOC Workshop 4 as outlined in Section 2.4. These include energy and range, communications, onboard sensor processing, and sensors and sampling. The science sensors and sampling will be address within NZOC Workpackage 5, but as noted in Section 3.1.1 these sensors and sampling systems must be as low power as practicable.

The following sections will review progress on these challenges over the coming decade.

[13] See https://sgp.fas.org/crs/weapons/R45757.pdf

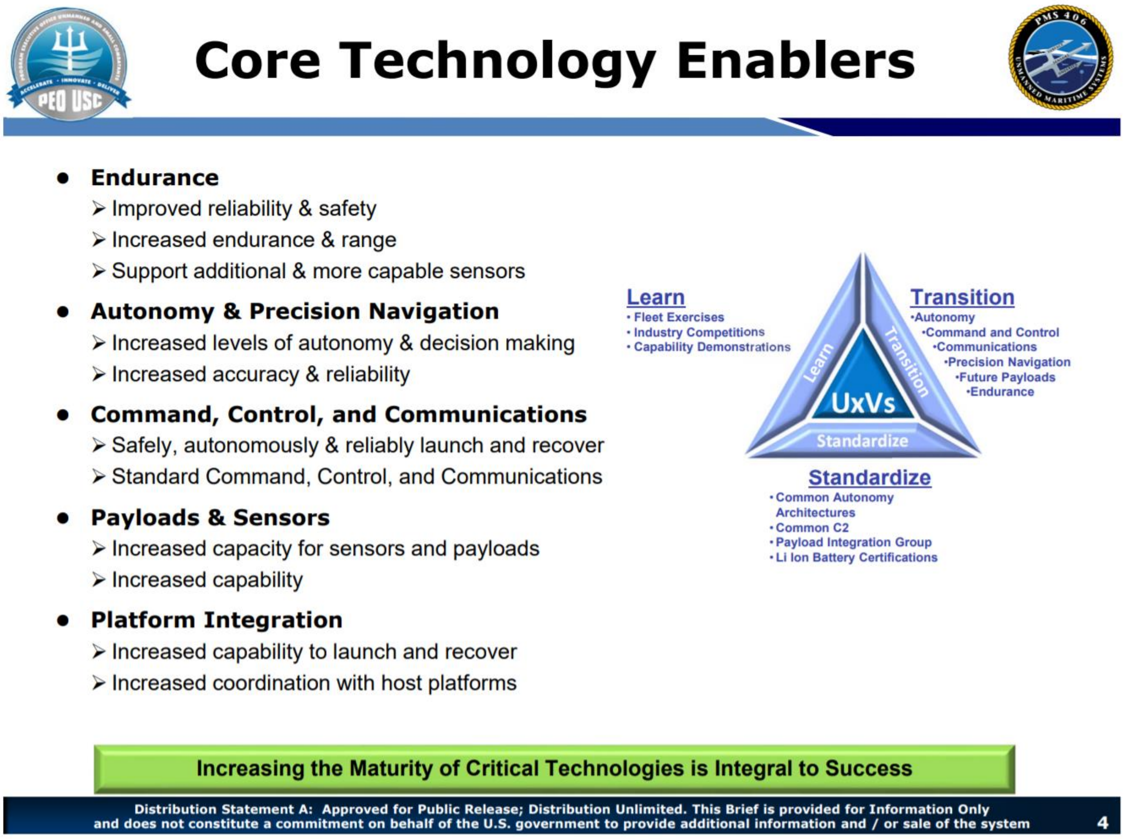

Figure 4. Source: Slide 4 of briefing by Captain Pete Small, Program Manager, Unmanned Maritime Systems (PMS 406), entitled "Unmanned Maritime Systems Update," January 15, 2019, accessed May 22, 2019, at https://www.navsea.navy.mil/Portals/103/Documents/Exhibits/SNA2019/UnmannedMaritimeSys-Small.pdf?ver= 2019-01-15-165105-297.

3.1 Energy & Endurance

All platforms require energy for their operation. For USVs, this energy can be harvested from the environment using wind, wave or solar power. However, for AUVs, energy harvesting is not practical, and so AUVs are constrained by the energy they can carry. This limited energy restricts the operational range of AUVs, and the sensors that they can use. As noted previously, the option to resolve this issue to either reduce the energy requirement, increase the available onboard energy, or arrange to recharge the vehicle mid-mission.

3.1.1 Reducing the energy requirements

For AUVs the energy usage is conceptually split between the propulsion power (used to overcome drag) and the hotel load. The hotel load covers the power used by the onboard electronics and the sensor payload. If we apply some simplifying hydrodynamic assumptions, it can be shown that the maximum AUV range occurs when the propulsion power equals half the hotel power (Furlong et al., 2007). Thus, the endurance and range of an AUV is controlled by the hotel load. This is why gliders and long-range AUVs rely on low power sensors.

The hotel load can be reduced by turning the payload off when not required (e.g. during transit) or by reducing the sensor power. Turning the sensor off is a common strategy for subsea gliders but does increase the mission complexity. Options to reduce the sensor power are limited. You can either select the lowest power sensor (and hope its performance is adequate) or encourage the sensor manufacturer to optimise the system for low power. It is often technically easier to reduce the sensor power than to increase the energy on the AUV. However, this optimisation has to be done by the sensor manufacturer, and given the small market for the power optimised sensors, these developments are not always prioritised. However, as the market for marine robotics continues to grow, it is expected that the sensor manufacturers will focus on reducing the sensor power.

Alongside the hotel load, the required propulsions power of an AUV can also be reduced (albeit only slightly) by improving the propulsion efficiency and reducing the drag of a UUV. Both approaches effectively increase the speed of the AUV for the same input power. However, as the power is a function of velocity cubed, cutting the drag in half would only increase the range by 26% for the same input power. You could extend the range further by keeping the same forward speed and dropping the propulsion power. Although improving the hydrodynamics and propulsion efficiencies is useful, the scope for increasing range through these improvements is limited, assuming the vehicle has been reasonably well designed.

Over the next decade, it is likely that there will be marginal improvements in the hydrodynamic and propulsion performance, but these will not have a dramatic effect on performance. Likewise, the sensor manufacturers will produce lower power systems. These will have a modest impact on the range and endurance but will not deliver the significant change required to overcome the issues identified by the NZOC Workshop participants.

3.1.2 Increasing the On-board Energy

Increasing the energy onboard the AUV will improve the range and can be accomplished by adding extra fuel space or using a higher energy density power source. Adding extra fuel space requires the AUV to grow in size, and the AUVs do not tend to have any spare payload capacity for energy. Increasing the size of the AUV will, in turn, increase the drag on the vehicle, thereby reducing the benefit of the added energy. As an example, the recently announced Hugin Endurance vehicle (2200 km range) is 10m long and 1.2m in diameter (and estimated to weigh approximately 10,000kg), while the Hugin superior (400 km range) is 6.6m long and 0.875m diameter (2200kg) with a very similar payload. Thus, a 4.5 fold increase in total vehicle volume produces a fivefold increase in range. However, the majority of the size increase will accommodate the extra batteries, and so the battery pack on the Hugin Endurance will be significantly larger than that of the Hugin Superior.

The energy density of the marine robots battery packs can also be increased by using different battery chemistries. Battery research and development is a massive area of investment as the world moves from fossil fuels to using renewable energy sources. The automotive and grid-scale energy storage sectors are investing billions of dollars, as are different national governments. The focus of the investment is to reduce cost and charge time, and improve cycle life, energy density and safety.

Current battery technology primarily relies on lithium for charge storage and can be configured either as primary (single use) or secondary (rechargeable) batteries. The current state of the art secondary lithium nickel manganese cobalt NMC ion cells use a liquid electrolyte and have an energy density of approximately 260 Wh/kg. These are about a third of the energy density of the Lithium Thionyl Chloride primary cells. Considerable developments continue with the classic lithium-ion packs, focusing on reducing cost, improving cycle life, and increasing energy density. Removing cobalt and nickel from the cell chemistries is also important due to the growing scarcity of these materials.

It is expected that the next major development in secondary battery technology will come from using a solid electrolyte in the cells. These solid-state batteries should be safer, have a higher energy density, faster charge rates, and longer cycle life. The technology is developing rapidly with massive commercial and state investment. However, the packs are still at the promising prototype stage, with Samsung creating a solid-state battery with an energy density of 900 Wh/L (Lee et al., 2020) and Ye and Li producing a solid-state battery with a cycle life ten times higher than a normal lithium-ion battery (Ye & Li, 2021). It is estimated that solid-state batteries will be in commercial production in four to five years.

Alongside solid-state battery research, there are also many other chemistries that are being explored. Examples include lithium-sulphur (Li-S) batteries, which have many useful properties that make them preferable for electric flight and AUV (Roper et al., 2016). However, the Li-S battery chemistry is still in the experimental stage. There are also more novel solutions, with Aluminium Seawater Batteries[14] being an example. These seawater batteries are effectively primary cells and work by corroding aluminium plates. They offer the promise of significantly increased energy onboard an AUV of between 4-5 times. However, the batteries are still something of an unknown quantity, and it is not clear how well they will perform on an AUV and what compromises would be involved in using them.

The final option for increasing the energy density is to replace the battery with a fuel cell. Fuel cells have been used on the JAMSTEC Urishima AUV (Sawa et al., 2005), the Hugin II, 3000 & 4500 until 2017 (Hasvold & Johansen, 2002; Weydahl et al., 2020) and are being developed for the new Cellula Solus LR AUV. Although fuel cells offer the promise of significantly increased energy density, they have a number of challenges. First, both the fuel and oxygen need to be carried on board the AUV. Second, the "combustion" products need to be stored internally to maintain the ballast and trim of the vehicle. Third, the technical complexity of the system is high. These three factors have meant that the fuel cell-powered AUVs have not been a commercial success to date (Weydahl et al., 2020).

It is expected that over the next 10 to 15 years, AUVs will continue to use batteries as their main power source. The investment in battery technology are likely to increase the energy density by a factor of 2 to 3 for rechargeable packs which will make them comparable to the current best in class primary packs. These developments are likely to mean long-range AUVs and gliders will transition to using rechargeable packs. The energy requirements are also expected to encourage long-range platforms to become larger to increase onboard energy storage.

3.1.3 Recharging mid-mission

A final method of increasing the range of the AUVs is to recharge the platform during an extended deployment, as effectively happens with high powered AUVs launched from a crewed ship. The challenge is to do this fully autonomously. AUV docking has been studied extensively since the early 1990s (Brighenti et al., 1998; Stokey et al., 1997), but docks have not achieved any significant uptake with AUV operators. The area where they are most likely to be used in the short term is through the uptake of field resident AUVs. Blue Logic has proposed a concept docking system for these vehicles[15] with their subsea docking station (SDS) see Figure 5. Kawasaki also has a concept docking and recharging station for their SPICE AUV[16] , which uses a different docking mechanism. Renewable powered docks have also been proposed. An example system uses a wave energy converter as described by Wallen et al (Wallen et al., 2019).

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[14] see https://www.l3harris.com/all-capabilities/al-h2o-aluminum-water-energy-modules

[15] See https://www.bluelogic.no/news-and-media/subsea-docking-station-sds-

[16] See http://www.khisubsea.co.uk/subsea-charging-station/

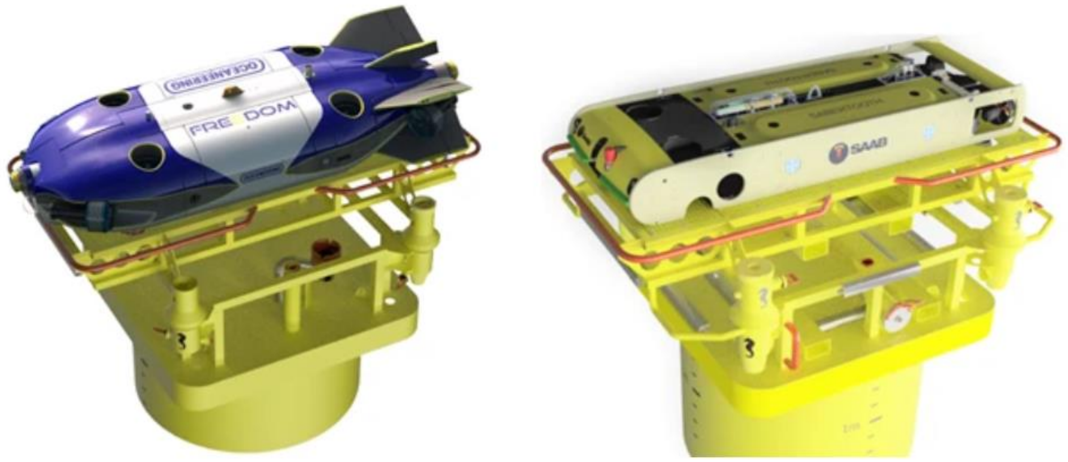

Figure 5. Blue Logic's Subsea docking station concept with a docked Freedom ROV (left) and a Saab Sabertooth (right).

Mobile docking systems have also been researched(Li et al., 2020; Page & Mahmoudian, 2019; Pyle et al., 2012) alongside the fixed recharge and data download docking stations. These mobile docking systems can be either incorporated in another subsea vehicle (Yan et al., 2020) or onto an uncrewed surface vehicle, as demonstrated by SeaKit with their USV being used to launch and recover a Hugin vehicle.

Docking stations have long been a solution looking for a problem, but it is expected that they will be in commercial use by the end of the decade. There are likely to be two main forms, with docks for field resident AUVs being the first and USV mounted docks being the second. There are also likely to be very specialist systems for docking small AUVs with XLUUVs or manned submarines, but these systems are not likely to be in the public domain. To enable AUVs to use these docks, they will need to be specially adapted to do so, and it is unlikely that a universal system will be available. Thus, the AUVs will only be able to operate within one docking ecosystem, which will limit growth in the area.

3.1.4 Increasing Range Conclusions

There are no easy solutions to increasing the range of an AUV with high sensor powers. A significant amount of research has been done looking at alternative energy solutions for AUVs over the last three decades. But, we still use either rechargeable lithium or single-use lithium cells to power most AUVs. Work has also been done to reduce the hotel load and effectively husband the limited energy available. However, the efficient use of energy is still bounded by the power envelope for the chosen sensors.

The concept with the most significant potential to increase range (and reduce the carbon cost) is to use either a USV or a set of fixed stations to recharge the AUVs. The USV recharging station is harder to achieve but has a number of advantages beyond just increasing range. It would also allow navigational aiding to the AUV, provide real-time comms to shore, act as a data relay and data store for data gathered by the AUV, and could be used to service the AUV cleaning any biofouling. Finally, if the USV captured renewable energy from the environment, the complete system would be renewable. However, it is a non-trivial problem to achieve, and so would require considerable investment to make it a reality.

3.2 Communications, command and control

Marine robots must be able to communicate to be effective. Thus, communication systems form a critical underpinning technology, whether on the surface using radio or satellite communication links or underwater using acoustic or optical modems. Unfortunately, as outlined by the participants of the NZOC workshop 4, the current communication systems are limited, which restricts the operational capabilities of marine robots. Developments in communication technology are expected to remove a number of these limitations and thus allow the vehicles to work in new ways.

The goal of many marine robots is to send data to and from shore; thus, Satellite communication is a crucial component of these ocean-observing systems. The data is used to track the position of the platforms, send back near real-time sensor data, and control the systems. These different objectives can be met using either a one-way or a two-way communication link. The required data rates will also vary, as do latency, satellite coverage, satellite transit repeat times, and power requirements.

There are currently several different satellite communications systems used in oceanography (Prior-Jones, 2008), with the primary systems being the Argos, Iridium and InMarSat networks. These systems target different markets, with the Argos network being used for low bandwidth, one way, global communication, e.g. in animal tags. The Iridium network is used for higher bandwidth, two-way, global communication. Gliders and small long-range uncrewed surface vehicles use Iridium for data and control. The network is considerably more expensive than the Argos system. Finally, InMarSat is used for high bandwidth, two-way communication. It uses a number of geostationary satellites and has full coverages to ± 65° and partial coverage up to ± 75° latitude. Although it can provide the high data rates needed for video, the geostationary satellites introduce considerable latency into the communication, and hence real-time remote control of ROVs is challenging.

The current satellite networks limit the capabilities of marine autonomous systems due to their bandwidth, latency and cost. However, we are on the cusp of a satellite revolution with the launch of next-generation Low Earth Orbit (LEO) satellite constellations. At the high bandwidth end, we have Starlink and OneWeb, which currently have partial satellite constellations in space undergoing beta testing. There are other constellations being planned with and InMarSat Orchestra and Amazon's Kuiper being notable examples. The high bandwidth LEO constellations will have an order of magnitude higher bandwidth than that typically seen by the current InMarSat systems. They will also provide full earth coverage at significantly lower latency and cost. These next-generation constellations are expected to be fully operational within the next few years and will enable USVs to be easily remotely piloted. The low latency will also enable ROVs to be flown from shore as easily as from a ship.

There are also many new entrants into the IoT satellite market putting up LEO constellations. These are aimed at low bandwidth users, with Lacuna Space and Swarm Space being examples. These IoT entrants will compete with the current Argos satellite systems. These are less mature than the OneWeb and Starlink systems, but it is expected that commercial platforms will be operating from the middle of the decade. Alongside the new entrants, the current satellite providers are also upgrading their system with Argos deploying the Kineis constellation and Iridium with Iridium Next. The new satellite constellations will open up new opportunities for platform and vehicle communication.

Alongside satellite communication to shore, marine robots also use radio systems locally. Examples of these systems include the 802.11 WiFi protocols for short-range high bandwidth communication and Freewave radios, as used by gliders, for more extended range links. The maximum range of the radio systems is limited by line of sight (and hence the earth's curvature). Hence, radio communication can only be used at short-range and is typically used between crewed vessels and the marine robot. It is expected that communication systems will continue to develop and will be integrated into new marine robots. However, they will not have the dramatic impact on operations expected from satellite communication developments.

Radiofrequency electromagnetic radiation gets significantly attenuated by seawater, and so radio systems do not work underwater. Hence, acoustic modems are typically used to communicate subsurface. However, they suffer from significant latency due to the speed of sound in water and have very low bandwidth, which decreases with increased range. But, the acoustic communication system is often combined with ultrashort baseline positioning systems to increase functionality.

Acoustic communication technology is mature, but as the encoding schemes are proprietary, they tie users into the equipment from the associated manufacturer. To overcome this lock-in, there is a push to get manufacturers to support common encoding standards like JANUS or the newer DSTL Phorcys[17] standard. If different manufacturers adopt these standards, it will enable communication between a wider pool of vehicles and simplify collaboration between systems. Given the maturity of acoustic communication systems, it is unlikely there will be any groundbreaking developments in the next 15 years that will radically change how marine robots operate.

Alongside acoustic communication, many manufacturers (e.g. Sonardyne's with their BlueCom) are working on underwater optical communication systems. These work by encoding a message into light pulses from a high power source, typically a blue LED. The signal is then received using an optical receiver, and the message is decoded. The absorption of light in water limits the signal range, and water turbidity and natural light from the sun can act as signal noise. Although high bandwidth is possible, the actual real-world communication range is limited. However, for specific use cases, optical communication works well. For example, the system was used as a communication link to live-stream a subsea broadcast from the untethered Triton submersibles as part of the Nekton mission to the Seychelle Islands. Different optical communication use cases will likely evolve, and their use will increase over the coming years.

Alongside changes in communication systems, there will also be huge developments in the shoreside command and control of marine robotics. These will integrate heavily with the data ecosystem addressed in NZOC Work Package six. Data from the platforms will feed into ocean digital twins, and in turn, the outputs of the digital twin will guide vehicle operations. The increased communication bandwidth, processing power on the vessels and software infrastructure developments will revolutionise the human-machine interfaces for the platforms. Current leaders in this field for ROV operations such as EIVA, Abyssal, and ROVCO provide examples of what is currently possible. The capability of these systems is only going to improve.

3.3 Autonomy - A Future look

3.3.1 Shared and Adjustable Autonomy

Shared autonomy refers to a paradigm that distributes intelligence between the human and the machine. It provides robots with the ability to function in the continuum between full teleoperation and full autonomy and enable operations that couple the complementary capabilities of humans and

[17] See https://www.unmannedsystemstechnology.com/2021/06/new-open-standard-for-secure-underwater-communications/

robots, improving the efficiency and effectiveness of human-robot collaboration (Selvaggio et al., 2021).

There is a long history of work in shared autonomy across various domains, including robotic manipulation, where the term was initially coined (Hirzinger et al., 1992), remote telepresence and assistive navigation. Some disciplines such as telerobotics, autonomous vehicles, and surgical robotics have set up specific classifications of autonomy levels, but they are hard to generalise for all applications. It seems more appropriate to define a spectrum instead of discrete levels of shared autonomy since the robot should ideally continuously vary its autonomy based on external information received from the human, the task, and the environment.

Although the term is often used in the context of physical human-robot interaction (proximal or remote), shared autonomy has increasingly assumed a broader meaning (Schilling et al., 2016), indicating all the techniques in which a human and a robot cooperate in reaching a common goal, both at the level of deliberation, i.e. when they collaborate to formulate action plans for the robot jointly, and execution, i.e. when they interact during action implementation.

Shared autonomy is different from and more sophisticated than shared control. Shared control is an established paradigm for combining human decision-making and robot precision capabilities. Although the system can perform some tasks autonomously, it leaves the human operator, who provides assistance through commands overlay, risk management and subtasks decomposition, the ultimate control over the system.

While in shared control, the autonomy level is manually designed and tuned by the human, shared autonomy assumes that the robot is capable of seamless adaptation of its autonomy level based on its own understanding of the human actions and intentions and the surrounding environment. Shared autonomy is more challenging than shared control, with several problems remaining open in complex applications. Determining the level of autonomy that a robot needs to exhibit based on the human's expectations and needs is a tough problem for the robot to solve. It requires an understanding of such expectations and accurate prediction of them as well as of how the environment evolves. The robot needs to adapt its behaviour based on both these elements, which requires careful balancing between potentially conflicting demands and a dynamical understanding of the importance of each source of information. Unstructured environments challenge shared autonomy approaches that require user, task and environment inference with ill-defined tasks, which are common in the maritime domain. This issue can be mitigated by developing strategies that make robots capable of online learning and real-time updating of their understanding of the user's goals and the task/environment. To this end, reinforcement learning and deep learning techniques can be instrumental, although they require a substantial amount of training data, which might be unavailable in hazardous environments. In going beyond the traditional vision of the human or the system jumping in and taking control of some actions when necessary, shared autonomy requires both parts to be able to engage in formulating alternative strategies and negotiating over them to reach truly joint deliberation and execution. New human-machine interfaces, likely based on natural language, will facilitate this collaboration and new interaction patterns.

As full autonomy in hazardous environments, such as the maritime domain, remains challenging, the shared autonomy paradigm will keep gaining traction as seen lately and remain prevalent for several years to come. Recent examples of shared autonomy in the subsea domain are human-robot collaboration for undertaking deep-sea manipulation (Brantner & Khatib, 2021), underwater cable maintenance tasks (Cho et al., 2021), path generation and data collection (Lawrance et al., 2019). We envisage that several developments will emerge in the next few years.

3.3.2 Explainability and Trust

Explainable AI (XAI) is a research field that aims to make AI systems results more understandable to humans (Adadi & Berrada, 2018). The term was first introduced by Van Lent et al. in 2004 to describe their system's ability to explain the behaviour of AI-controlled entities in military simulations and computer games (Lent et al., 2004). As the same authors indicate, the term they coined links back to early efforts made by the AI community in the '80 to explain how expert systems make decisions (Moore & Swartout, 1988).

With the decline of expert systems, the interest in XAI faded away, but recently the topic has received renewed attention from academia and practitioners due to the great success of machine learning (ML) techniques in several fields and their growing use in many real-world applications. ML is a crucial component in critical decision-making processes in areas as disparate as health care, law, and finance, but it has so far failed in providing detailed information about the chains of reasoning steps that lead to the final decisions, recommendations, predictions, and actions. This phenomenon, which relates to the opacity of the algorithms used in ML, is usually referred to as ML being an instance of "black-box" AI. Given the importance of the decisions made by ML algorithms, there has been increasing pressure from legal, ethical, and societal points of view to develop new AI techniques that can make decisions explainable and understandable to their users.

Technically, there is no standard and generally accepted definition of explainable AI, and, in the literature, other terms are broadly used to express the same concept, such as transparency, intelligibility, and interpretability. In addition, although the initial focus has been on explaining ML techniques, the idea has gradually been expanded to regard all sub-areas of decision-making, including AI planning and agent technology (Chakraborti et al., 2020).

Based on the literature in this field, the need for explaining AI systems usually stems from (at least) four reasons, which can also overlap (Adadi & Berrada, 2018): the need to provide justifications for decisions taken (need to justify), they need to understand how the system works to prevent failures and correct flaws and vulnerabilities (need to control), the need to improve the models used via a continuous iteration between the system and its users (need to improve) and, finally, the need to gain new insights into the problem at hand based on what the system has done to solve it (need to discover). It is also worth noting that, depending on the application, explanations can be required at different times: i) ex-post, i.e. after the system has reached a decision, to provide justifications; 2) ex-ante, i.e. after the system has proposed a solution but before its actual implementation, to verify/assess such solution; or 3) during the decision process, i.e. when the system and the human interact to agree on a joint decision, to facilitate negotiation.

Ultimately, explanations are needed to build trust in the machine and its decision making. As trust rests on understanding, the more the users comprehend and support the system's decisions, the more they will be inclined to adopt the proposed solutions. Trust towards robotic systems, in particular, depends on many factors such as the context, the application, and several individual circumstances such as the user's attitude and experience. However, the transparency of the system behaviour, intended as the human understanding of what the robot is doing at any time, why, and what it will do next is a crucial aspect to consider in fostering trust in autonomous systems.

XAI is an inherently multi-disciplinary field that lies at the intersection between AI, social sciences, and human-computer interaction (HCI). In the area of AI and ML, new paradigms are needed to make algorithms scrutable to humans and decide which data need to be collected for this aim. However, to produce artificial explanations, it is crucial to understand how humans explain decisions and behaviours to each other (Miller, 2019), which pertains to social sciences. Finally, once the building blocks for providing explanations are ready, how the system coveys them to the user is equally fundamental. This is the realm of HCI. The way in which explanations are presented depends on the application and the expectations of the end-users. Many different possibilities are available, ranging from natural language interfaces to visualisation and augmented reality.

The importance of XAI in operations at sea and underwater cannot be stressed enough. As discussed previously, uncrewed systems operating in this domain are usually equipped with a high degree of autonomy to allow long-term operations in an uncertain and hostile environment. As such, they use sophisticated ML and planning algorithms, which are generally opaque to scrutiny. At the same time, however, such systems are always supervised by human operators who monitor the missions at a distance. It is crucial that these operators understand what the robots are doing at any point in time and support their decisions and actions. Since in extreme environments, strict safety standards are in place, errors on the part of the robots would not only harm the mission itself but also deter the adoption of such systems in the future, undermining the trust in them. When error tolerance is low, XAI becomes an essential tool for the human operator to validate and embrace the robots' behaviour.

Work in XAI for marine robots will build on the general developments of this area, although some specific effort in this area is already underway. In particular, the UK Robotics and Artificial Intelligence Hub for Offshore Robotics for Certification of Assets (ORCA Hub) is investigating techniques to increase robotics transparency by empowering the robot to answer the following questions: a) "Why did you do that?" (Explain the robot's behaviour models with various scrutability levels); b) "What are you doing?" (Explaining activity and reporting what the robot is doing); c) "What do you sense?" (Explain the environment); d) "What if you do this instead?" (Counterfactual reasoning) (Hastie et al., 2018). The ORCA Hub is also carrying out work on multi-modal interfaces that adapt to the user's cognitive load.

In general, as the adoption of autonomous systems in hazardous environments depends on trust in them, we expect to see significant activity and many new developments in the area of XAI for marine applications, in all the subfields involved, i.e. AI and ML algorithms and models, HCI interfaces and social sciences acceptability studies. Given its multi-disciplinary nature and the complexity of ML and AI techniques, XAI is a challenging field. Difficulties get exacerbated in the subsea domain because human operators must handle multi-objective and multi-vehicle missions while simultaneously suffering delays in communication and facing uncertainty over the environment and the status of several remote high-value assets. We envisage that scenarios in this field could serve as benchmarks for testing the robustness of XAI solutions developed by the scientific community in all the other relevant areas.

3.3.3 Robust Autonomy

Robustness applied to autonomous systems is a broad concept: it is the capacity to withstand human errors in the direct operation of the systems as well as in the modelling of the domain and the goals; it is also the ability to deal with uncertainty, unmodelled phenomena and to resist cyberattacks. For a fleet of marine robots, robustness factors in the physical integrity of the vehicles, the minimisation and mitigation of identified risks, and the availability of mission planning technology that adaptively prioritise achievable objectives. In what follows, we will analyse the most relevant facets of robustness for autonomous marine robots.

3.3.3.1 Persistent Autonomy

As discussed above, autonomous robotic operations become cost-effective in marine operations when they can last over long periods of time. The current trend is to extend missions from hours to days and months. This will be possible by developing and adopting long-endurance vehicles, by recovering vehicles for recharging or battery swapping, and by allowing vehicles to dock to a recharging station.

Autonomy solutions to support persistent autonomy for solo and multi-vehicle missions exist but tend to be brittle and often require support from the human operator. Scalability is a significant challenge to centralised planners, as the task decomposition and allocation problems can quickly become very challenging for complicated activities and a large set of vehicles and tasks. Decentralised solutions exist, but they face challenges in communicating the minimum required information for approximating solutions to complex and interdependent tasks. We envisage that further developments in AI planning will be needed from an algorithmic point of view to support long-term autonomous operations. New solutions for autonomy will likely involve adaptive planning and machine learning, which we will discuss in what follows.

3.3.3.2 Learning and Adaptive Planning

Machine learning contributes to marine autonomy in several ways, including perception, navigation, control, and decision making. Although the most crucial ML contributions have been at the vehicle's sensor processing level for perception and localisation purposes, planning systems have also benefitted from the advancements offered by ML.

Since adaptive planning is based on updating plans in the face of new information, better perception has led to more efficient adaptive planning systems. In addition, planning architectures that directly map sensor inputs to vehicle actions have started to gain some traction in the subsea domain. For example, Jamieson et al. (2020) propose a novel approach to vision-guided exploration using a human-robot team that is effective even in the presence of strong bandwidth constraints. In particular, a robot recognises visual phenomena that might be scientifically interesting, transmits images of them to scientists for clarification as needed, models where more of them might be found, and adaptively plans a trajectory accordingly. This approach is an instance of active learning where the robot learns a mapping from observations to reward in the context of a POMDP planning formulation for vision-based scientific exploration.

Advances in ML have also been leveraged to solve control problems. Parras et al. (2021), for example, make use of recent advances in deep learning to efficiently solve the optimal control problem applied to AUV motion planning in the presence of disturbances.

As in other areas of robotics, we expect to see an increase in the use of ML techniques to underpin the autonomous behaviour of marine vehicles. However, progress in the area is inseparably linked to advancements in explainable AI as the end-users of marine technology would not be prepared to use "black-box" solutions for underwater operations. As a result, we expect to see the two fields grow hand in hand in the next few years.

3.3.3.3 Safe and Risk-Aware Autonomy

When autonomous systems are deployed in real-world environments, it is of the utmost importance to consider and, ideally, guarantee safe runtime operation. Since these systems operate in highly uncertain and dynamic environments, it is crucial that the model and quantify environmental uncertainty, understand its impact on system dynamics, predict the motion of other entities present in the environments, and make safe, risk-aware decisions.

The topic of safe, risk-aware autonomous systems has seen a dramatic increase in importance over the last few years, as these systems are being deployed almost daily within safety-critical applications such as, for example, self-driving vehicles, autonomous undersea and aerospace systems, service robotics, and collaborative manufacturing. However, widely used algorithms for autonomy are beginning to showcase fundamental limits and practical shortcomings. An excessive risk taken by these algorithms can lead to catastrophic failure of the overall system and may put human life in danger. Many AI methods used today do not attempt to quantify uncertainty; they do not assess the risks that uncertainty imposes on system safety and success; they do not guarantee bounds on this risk, and they do not perform these assessments in real time.

Only in the last couple of years, a new generation of risk-aware AI algorithms and autonomous systems have begun to emerge. Key to these methods is their ability to account for uncertainty and risk of failure during their online execution, their capabilities for proactively quantifying and mitigating risks against task goals and safety constraints, and their ability to offer formal guarantees, such as bounds on the risk of failure. Emerging risk-bounded methods often operate on models of uncertainty, specifications of intended outcomes, and specifications of acceptable risks regarding these outcomes. These models and specifications are diverse. Uncertainty models may be probabilistic, set bounded, or interval based. Intended outcomes include goals achieved, deadlines met, safety constraints respected, required accuracy in model estimation and perception, and rate of false positives. Specifications of acceptable risk include risk bounds and acceptable costs of failure. These intended outcomes and acceptable risks can apply to individual AI components, such as policy and action learners, image classifiers and planners, and the aggregate systems as a whole.

In the next few years, we expect to see further progress in this area, especially in risk-aware task and motion planning, robust and adversarial learning, certifiable and risk-aware perception, localisation, and mapping; robust task monitoring and execution under uncertainty, formal methods for monitoring and verifying uncertain systems, and robust control of intelligent systems.

3.3.3.4 Standardisation and Interoperability

While there is an ample choice of downloadable tools for perception, this cannot be said for the fundamental modules needed for autonomy, such as planning (in its different incarnations of mission, task, and motion planning), monitoring, execution, and diagnosis. Even less attention has been received to their integration in plug-and-play autonomy architectures capable of working robustly in a variety of domains. The lack of a standard autonomy architecture shared by the community has hindered progress in this area. Different techniques live in isolation from one another, and the field is highly fragmented.

We anticipate seeing growing effort towards the standardisation of architectures for autonomy, in the same way as this happened in other fields of AI. Harsh environments such as the marine one could serve as an ambitious bench test for autonomy. A standard architecture would likely be ROS-based to maximise usability and modular so that each component can be chosen among a set of possible ones based on the domain's characteristics. It would probably present a hierarchical structure, with a perception layer at the bottom and a high-level deliberation layer at the top, which will call learned skills sitting at lower levels as appropriate according to the situation.

Standard architectures and interfaces would facilitate interoperability, which is the ability of software or hardware systems to operate together successfully with minimal effort by the end-users, and it can be categorised into levels, types, or degrees of interoperability. A mature and stable interoperability framework between unmanned systems, human operators, and legacy platforms is seen as crucial for unleashing the true potential of marine robotics (Costanzi et al., 2020). The current multi-vendor, multi-protocol solutions are hard to interoperate without common mission control interfaces and communication protocol schemes. In addition, the underwater domain presents significant challenges that cannot be satisfied with the solutions developed for terrestrial networks.

Currently, interoperability is receiving a great deal of attention as stakeholders share the view that marine vehicles must be fully interoperable in order to enhance their efficiency, reliability, and survivability, reduce mission costs, and lower the human burden. As a result, we foresee important developments in several areas, including the capacity to concurrently communicate with, manage, and elaborate different data formats; the ability to quickly change modules and payloads in a plug-and-play manner; the development of open standards, architectures, and equipment; and the development of interoperable, realistic, integrated modelling and simulation environments.

3.4 Commercial & Stakeholder priorities and opportunities for collaboration

There is considerable commercial interest in surveying areas of the North Sea. This is to assess the impact of decommissioned oil and gas infrastructure and perform site surveys for offshore renewables. As shore launched long-range AUVs provide an ideal tool for these surveys, we could work with industry to align technical development of the Autosub Long Range platform to support commercial and science objectives. These surveys could be further enhanced by operating the AUV in tandem with a USV acting as a communication and navigational aid. This provides another opportunity to work with industry. The final technical area of collaboration would be to work with partners on the launch and recovery of AUVs from USVs and fixed docking stations.

As commercial companies transition to using more remotely piloted USVs and connected crewed vessels, they will send back more data to shore. Some of this data could be useful to the oceanographic community, and the commercial companies may be willing to donate it to support ocean science. Thus, there is an opportunity to engage with commercial partners to build supporting infrastructure that enables simple third party data ingestion. This data could then form part of the input stream into the data ecosystem outlined by NZOC Work Package 6. Once such a portal is built, other contributors could use it, such as yacht owners and fishing vessels. This would also help engage the wider ocean-going community as part of the drive towards citizen science. Alongside the ingestion of native vehicle sensor data, there are also opportunities to add Ferry Box style sensors suites to commercial to enhance the oceanographic data collected.

Alongside the possibility of donated data, many new companies also operate a data as a service model, e.g. XOcean and Saildrone. These companies could be contracted to collect specific oceanographic data for the community. This approach is being followed by Saildrone and NOAA-PMEL, who have formed a Public-Private partnership to advance regional ocean observing capabilities (Meinig et al., 2019, p.). There will likely be many new opportunities within this data as a service space, and the third-party data ingestion portal (mentioned above) would simplify this engagement. There will be multiple contracting options, from bespoke missions to piggybacking onto transit periods or commercial operations. The key challenges to working in this space are more contractual than technical, and so work needs to be done to ensure the contracting process is efficient.

3.5 Regulatory and legal issues

The regulatory and legal issues will primarily be dealt with in NZOC Workpackage 2. However, there were a number of issues raised as part of the NZOC Workshop 4, which are worth noting here as they add extra hurdles to the use of marine robots.

Regulatory monitoring typically prescribes the techniques needed to collect environmental data, and these usually require a ship. This presents a challenge to adopting Marine Robotic based measurement techniques, as these may not follow the protocols listed in the regulations. For example, fish stock assessment was explicitly mentioned as an issue in the NZOC Workshop 4. The new robotic methods will also need to be compared to the current best practice to: ensure the data is of acceptable quality; and to understand how to integrate it into the existing time series data. The results of these studies will need to be reviewed by relevant international experts before any changes to the regulations could be proposed. Thus, the process of moving from ship to MAS based techniques could be both time consuming and expensive.

Alongside regulations about monitoring techniques, it is not universally accepted that Marine Robots can be operated in the Exclusive Economic Zones (EEZs) of different nations. For example, India has a ban on the use of Iridium satellite communication[18] , thus preventing the use of ocean gliders. It is also not entirely clear that nation-states will allow access to their territorial waters without having an "observer" on board. Currently, this is not a significant problem for the likes of ocean gliders but could become more contentious as we move to more capable remotely controlled or autonomous vessels. There are issues around biosecurity that would need to be considered for certain operations. For example, research ships entering the water of the Galapagos islands need to have their hulls scrubbed beforehand. It is not clear how this would impact a long-range glider or surface vehicle.

Finally, the issue of liability around marine robotic systems is not clear. Although these issues have been considered, for example, by the Maritime UK in their "Industry Code of Conduct for Maritime Autonomous systems", the actual regulations are still being developed. Thus, companies like Ocean Infinity are approaching these issues cautiously and are employing fully trained seafarers in their remote control centres to ensure compliance of their robot vessels with collision regulations (ColRegs). It is likely to be many years before we have complete clarity in this area.

3.6 Gap Analysis

Over the next 15 years, the industrial and defence sectors will not develop marine robots to fulfil all the identified science requirements and carbon reduction targets. This is first because some of these challenges are particularly difficult to solve and second because they do not share the same requirement as the ocean science community. This section addresses both issues to highlight the likely gaps in marine robot developments. It also identifies areas where the science community will need to develop the technology itself.

The first major challenge involves the deployment of heavy infrastructure such as Rock Drills, deep-diving scientific ROVs, seismic streamers, and mooring strings. To undertake these deployments from a marine robot is hugely challenging. Although not impossible (Ocean Infinity intends to deploy ROVs from their remotely piloted USVs), the deployed system will need to be specifically designed for remote deployment, which will add expense and complexity. The operations will also be inherently higher risk as there will be no one to fix any issues that arise. The deployment will need to be from a large high power USV. As most of the carbon impact comes from the size and power of the vessel, it makes little difference if it is remotely piloted or crewed. Thus, it is expected to be simpler and more economical to use a low carbon crewed vessel for these applications in the future.

As noted in Section 2.4, the second major challenge is associated with taking, analysing, and storing samples on board a vessel. Again, as with deploying heavy infrastructure, this is not impossible using

[18] See DGS Order No. 02 of 2012

a large, remotely operated USV. However, the infrastructure required to take biological, sediment and water samples remotely is complex. But, the real challenge comes from processing the samples once on board. This could involve analysing the sample before it degrades, running an incubation experiment, removing the sediment from a piston core, or preserving the sample for transportation back to shore. This on board processing challenge is extremely difficult to solve given the variety of samples taken and analysed. Unfortunately, Industry is not generally focused on sampling methods, so commercial developments cannot be leveraged to address the processing problem. Thus, the simplest solution will be to use a low carbon crewed vessel to continue the traditional sampling methods. While at the same time, autonomous sampling techniques should be developed to replace some of the traditional methods.

One sampling area which could be partially migrated to autonomous methods is that of hydrographic sections. The current best practice for undertaking hydrographic sections is laid out in the GO-SHIP Repeat Hydrographic Manual[19]. Each section involves repeated casts of a CTD rosette to measure the properties of a vertical section of the water column. This is performed using a high accuracy CTD measuring temperature, conductivity & dissolved oxygen. Also, during the cast, water samples are collected to calibrate the CTD data. The conductivity measurements are compared to standard seawater using an on board salinometer, and the dissolved oxygen is compared to the experimentally determined value using Winkelman titration. This is done to ensure that the CTD data meets the stringent World Ocean Circulation Experiment (WOCE) requirements. The water samples are analysed to provide other measurements.

Conceptually an AUV could be built with the necessary range and sensors to perform hydrographic section measurements. This would not provide the full GO-SHIP data set, but it would cover the main physical oceanographic property measurements that underpin the Argo array. Although this may appear fanciful, the decommissioned Autosub 3 vehicle could have been adapted to have a range of thousands of kilometres, was equipped with the same CTD used on the ships Rossette and had lots of free flooding space for water samples. Thus, a similar vehicle could be readily developed with the necessary range and sensors. The main technical challenges will be in calibrating the sensors. This may be possible using a lab-on-chip system or may need to be done by taking water samples. The final scientific challenge will be optimising the AUV approach to maximise data quality and ensure it can be integrated into the existing hydrographic section data sets. With suitable funding, it is expected that this could be achieved within the next decade.

One area that the commercial sector has limited interest in developing capabilities is under-ice operations. The defence sector does have a growing interest in this area, but they currently rely on academia and oceanographic research institutes to develop the capabilities they use. Also, any technology they may use is often not commercially available. Thus, the oceanographic community will need to continue the developments of under-ice capabilities. This will include ice coping behaviour for AUVs and gliders, alongside under-ice navigation techniques and communication methods. Without investment in this area, the scientific community will not be able to measure critical ocean processes.

Finally, although the commercial sector is producing hovering and light intervention AUVs for their needs, these are likely to be shallow rated and not suitable for the variety of ocean science work. Thus, there is a need to develop a deep-diving hover capable AUV for close up inspection that can be rapidly adapted for varying scientific needs. A hovering vehicle could partially replace deep-diving ROVs and thus allow operation from smaller research vessels or USVs. The hovering vehicle would

[19] See https://www.go-ship.org/HydroMan.html

also act as a base platform for autonomous intervention and sampling. These capabilities would be added as the vehicle's software capabilities are improved over the next decades. To complement the hovering AUV, a deep autonomous crawling vehicle would also provide valuable capabilities to the community. It would allow the vehicle to perform in situ rate experiments without the need to return samples to the surface. The vehicle could also be rapidly developed using the building blocks of existing marine robotic platforms.

There are a number of development gaps in the carbon reduction and science requirements that industry and other stakeholders will not address over the coming decades. Deployment of heavy infrastructure and sampling are particular operations that will be hard to achieve without a crewed research vessel, and so it is not expected that this will change over the coming decade unless there are significant changes in sensor technology. Some sampling requirements can be more simply migrated to autonomous platforms, with hydrographic sections being identified as a target area. Also, under-ice operations and new vehicle developments will need further investment to deliver new critical capabilities to the oceanographic community.

4 The carbon cost of operations

4.1 Carbon cost calculations

Calculating the carbon impact of marine observing systems is non-trivial, and even for the same type of observation, the impact is highly dependent on the specific deployment. For example, deploying a glider for six months from Scotland has a lower carbon impact than undertaking the same deployment in the Southern Ocean. However, it is possible to produce rough estimates of carbon impact for different activities, allowing us to draw broad conclusions while accepting that the underlying figures have significant uncertainty.

This section estimates and compares the carbon impact of different marine robots alongside that of a research vessel like the RRS *James Cook*. To simplify the calculations, we have made the following assumptions.

- The carbon impact of the logistics, travel, piloting and data ecosystem is ignored.
- The CO_2 equivalent produced from the grid as part of the energy generation uses the UK's 2030 target of 100g per kWh at the wall socket.
- The conversion efficiency from the wall socket to useable energy stored in a battery is 85%. These losses result from inefficiencies associated with the charging electronics and the cells equivalent internal resistance, etc.
- The embodied carbon for MAS and ships (excluding the battery pack) is proportional to the vehicle weight and is the same for all systems. We also assume that this $kgCO_2e$ / kg is the same as that typically seen in electric cars. This is a gross simplification and is likely to contain a considerable amount of error. However, as the manufacturing and material processes are similar, one would expect the $kgCO_2e$ / kg to be of a similar order of magnitude. This was deemed adequate for this analysis.
- The embodied carbon for primary (single use), and secondary (rechargeable) batteries are the same per kWh of capacity. This assumption was made as no data could be found on the CO_2 cost of primary lithium packs. However, as they use similar components and processes it is not unreasonable to assume they would have a similar embodied carbon. Using kWh capacity was chosen as the higher specific energy density (kWh / kg) would partially compensate for the lower volume production and hence higher embodied energy per kg.

4.2 Embodied carbon

The CarbonBrief undertook an analysis of electric vehicles in 2019 and updated it in 2020 entitled "Factcheck: How electric vehicles help tackle climate change". This report estimated the embodied CO_2 per km for a Toyota Prius as 38g/km with an estimated vehicle life of 150,000km. Thus, the estimated total embodied carbon is 5700 kg. As the Prius weighs 1300 kg, this gives an embodied carbon of 4.4kgCO_2e per kg of car mass. This figure is likely to be a lower bound for a marine robot, so a value of 5 kgCO_2e of embodied carbon per kg of robot mass is used in this analysis.

Battery manufacture is an expensive process and embodies a considerable amount of CO_2. Numerous researchers have tried to estimate the cost for secondary lithium batteries (Lutsey & Hall, 2018), with battery production emissions ranging from as low as 30 to close to 500 kgCO_2e/kWh. Thomitzek et al. (Thomitzek et al., 2019) took a different approach, and they estimated the embodied energy for battery production in Watt-hours for manufacture per Watt-hour of secondary battery capacity. This approach has the benefit of allowing you to use the local grid carbon intensity to calculate the carbon impact. The authors estimated the embodied energy as 1150 Wh to produce 1 Wh of secondary battery capacity. The UK's 2030 electric generation carbon intensity would give a carbon cost of 115 kgCO_2e/kWh, which broadly aligns with the figures reported by Lutsey & Hall. Given the spread of embodied carbon values, we have assumed a carbon cost of 150 kgCO2e/kWh of capacity for the analysis. We believe this is likely to be representative of the embodied carbon based on 2030 grid carbon intensities.

4.3 "Fuel" carbon cost

The variable carbon cost for an operation is assumed only to include the "fuel" cost. This CO_2 cost of the "fuel" is 1) produced by the grid in generating the electricity to recharge the vehicle's battery, 2) embodied in the primary battery pack, or 3) generated by burning fossil fuels. The carbon impact of the different energy sources is shown in Table 1.

"Fuel" Source	Carbon impact (kg CO_2e / kWh)
Lithium rechargeable	0.118 (UK grid carbon intensity 2030 and 85% charging efficiency)
Marine Gas Oil (MGO)	0.54[20]
Lithium primary	150 (embodied carbon as noted above)

Table 1 Carbon Impact for different fuel sources

Table 1 clearly shows how poor lithium primary batteries are at powering vehicles. It also shows that although MGO produces a lot of CO_2 it is 4.5 times the output of lithium rechargeable batteries per kWh. However, if we included the embodied carbon in the calculations, the rechargeable batteries would look considerably worse than the MGO. Using our assumptions, it requires the battery to be recharged 321 times before the carbon impact has reduced to the same as that of MGO (i.e. 0.54 kg CO_2e / kWh).

4.4 Estimated carbon cost per km for different platforms

The embodied and variable carbon costs for a selection of oceanographic platforms were calculated, and the results are shown in Table 2. The table lists the vehicle, the associated Mass and a number of estimated values. Column three gives the CO_2 equivalent released per km travelled by the vehicle. Column four gives the ratio of the "fuel" CO_2 released to the embodied CO_2; this is useful for vehicles that take their fuel with them as it shows how effectively the embodied carbon is utilised.

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[20] Assuming: MGO energy density = 42MJ/kg; CO_2 per kg MGO burnt = 3.15 kg; Engine efficiency = 50%

Note this is not applicable to energy harvesting surface vehicles. The final column shows the CO_2 equivalent released per km per kg of the vehicle mass. This value shows how efficiently the platform moves each kg of the vehicle. The full details of the analysis are presented in Appendix A.

Vehicle	**Mass (kg)**	**CO_2e / km**	**Fuel CO_2e / embodied CO_2e**	**gCO_2e / km.kg**
Slocum Glider - Rechargeable	65	25g	0.007	0.385
ALR6000 - Rechargeable	600	177g	0.011	0.295
ALR1500 - Rechargeable	780	332g	0.006	0.425
A2KUI	2000	603g	0.034	0.301
Hugin Endurance	10000	1.86 kg	0.013	0.186
Waveglider SV3	155	40g	0.000	0.254
Autonaut 5m	280	68g	0.000	0.243
Saildrone Explorer	750	135g	0.000	0.180
Slocum Glider - Primary	65	250g	22.15	3.859
ALR6000 - Primary	600	2.6kg	25.00	4.333
ALR1500 - Primary	780	2.6kg	18.46	3.372
James Cook	5401000	90.0 kg	6.50	0.017

Table 2 Comparison of carbon impact for different vehicle deployments

The results shown in the table are surprising but allow us to draw the following broad conclusions.

- The RRS James Cook has the lowest gCO_2e/km.kg of all the systems. This result may seem surprising, but it is assumed that the RRS James Cook has the longest expected lifetime range (75 times larger than an ALR) and hence can spread the embodied CO_2e over this significant service life. This is also shown in the ratio of the Fuel CO_2e to Embodied CO_2e.
- Using primary batteries has a significant impact on the CO_2 emission of a marine platform, with the CO_2e being roughly ten times higher than a rechargeable battery pack. However, this is based on the assumption that primary packs have the same embodied energy per kWh as secondary packs. If we assumed the embodied energy was the same per kg, this would reduce the difference by a factor of approximately 3. The results also depend heavily on how many times the secondary battery is used. The more charge/recharge cycles of the secondary battery the longer the range the embodied CO_2e can be spread over. This can be seen by the difference in the CO_2e per km for the ALR6000 and ALR1500 using secondary packs. Both vehicles are assumed to have the same service range, but the ALR6000 battery would need to be recharged about 2.5 times more than the ALR15000 pack.
- This modelling predicts that 35 ALRs using primary batteries would generate the same CO_2e on a km per km basis as the RRS James Cook. Also, a Slocum glider using primary batteries would generate a similar level of CO_2e per km as an ALR using secondary packs.
- Surface vehicles such as Wave Gliders, Autonauts, and Sailrdones provide very low CO_2e as their propulsion and electrical power are produced solely from renewable sources. The gCO_2e / km range of 40 to 135 could be significantly reduced by utilising the vehicles more, and hence increasing their lifetime range.
- Maximising service life will minimise the embodied CO_2e per kilometre travelled.
- Using rechargeable batteries significantly reduces the "fuel" CO_2e. The benefits of rechargeable packs are maximised by increasing the number of recharge cycles they go through. However, for long-range vehicles such as gliders, the potential number of charge cycles is limited by the vehicle's service life, e.g. a ten-year service life would have a

theoretical maximum of 40 three-month deployments. However, in reality, the actual maximum is likely to be half of this.
- The primary benefit of moving to MAS is not a result of using battery power; it is about moving to smaller systems that require less energy to operate. Thus, using fossil fuels on small marine robots is likely to have lower carbon than relying on a battery pack due to the difference in embodied energy.
- Finally, a combination of an uncrewed surface vehicle recharging an AUV would likely minimise the CO_2 per km. For example, a combined an ALR6000 AUV and an Autonaut 5m USV would have the same CO_2e per km as a Slocum using primary batteries.

4.5 Caveats on the analysis

By its nature, this analysis is very crude. It provides broad trends but does not capture the detail accurately. For example, the embodied CO2e per kg is assumed to be the same for a research vessel, a Slocum glider, and a long-range AUV. These use different materials, have different manufacturing techniques, and are produced in different volumes. Thus, it is highly unlikely the embodied CO_2e is going to be the same.

The analysis has also ignored all the logistics, preparation and piloting carbon costs for a mission. These carbon costs are likely to dominate for certain platforms performing certain missions. For example, using this analysis, a two-week deployment covering 500km from Orkney with a rechargeable glider would have a CO_2e cost of 12.5kg. However, this would be dwarfed by the CO_2e costs associated with transporting the glider to the mission site, sending staff up to launch and recover the glider, and using a small diesel-powered boat for the launch and recovery. Thus, for some types of missions focusing on this narrowly defined mission CO_2e cost makes little sense. Instead, a holistic analysis that includes the ancillary carbon costs should be undertaken.

5 Proposed Roadmap

Marine Autonomous Systems, and autonomy in general, has the potential to reduce the carbon cost of oceanographic science. This reduction is due to the smaller size of marine robots, leading to lower embodied carbon content and lower operational carbon cost. However, marine robots are currently limited in the types of science they can support. Thus, to maximise the opportunity to reduce carbon costs that MAS presents, it will be necessary to extend the scope of science that the vehicles can support. This will involve identifying specific science applications that marine robots could reasonably undertake and then investing in the supporting data ecosystems, platforms design, sensors, and on board and off-board autonomy to deliver these new use cases. Outside of the drive to reduce carbon, we are moving towards closer coupling of in-situ sensing, remote sensing and modelling, and integrating all measurements into a global ocean observing system. So, all marine robot developments should be aligned to support this goal.

To achieve this transformation towards low carbon oceanography, it will be critical for scientists, engineers (both platform and sensor), and data managers to work together as one team with the necessary funding to support the activities.

5.1 General recommendations

The capabilities of Marine Autonomous Systems are changing rapidly and so predicting the future trends over the next 15 years is non-trivial. New ideas, platforms and sensors will emerge, which will unlock new opportunities. Thus, it will be necessary to review progress and re-plan the developments as new information becomes available. As such, we have split the road map into five-year phases, with re-planning occurring at the end of each. The phases will consist of four basic activities (see Figure 6) aimed at extending the capabilities of Marine Autonomous Systems for ocean science.

- **Technology pipeline** - This involves lower technology readiness level (TRL) development activities that underpin new platform capabilities and science applications. The pipeline will include reviews of existing capabilities from other domains and short design studies. The low TRL development work, reviews and design studies would form the precursor activities for subsequent capability developments.
- **MAS capability development** – This phase will focus on the underlying platform capabilities. It would include, as an example, enhancing communication and energy systems, improving autonomy and situational awareness, and increasing reliability.
- **MAS science extension** – This would aim to extend marine robots' usage into new operational areas. It would look at adapting and optimising existing platforms to enable them to undertake these new operations and would include demonstration activities. The focus would be moving existing ship-based science onto marine robots to reduce carbon. It is likely that the MAS approach will initially be more expensive and of lower data quality than the existing ship-based methods.
- **MAS science optimisation** – Given that marine robots may produce lower quality data initially, it will be necessary to fund extended MAS transition activities. These will need ring-fenced funding to use marine robots to deliver real-world science alongside ship-based methods. These extended transition activities would enable optimisation to reduce cost and increase data quality while also providing opportunities to conduct cross-comparison between the methods. This would help with the transition from the ship-based to the MAS-based methodologies and assist cultural change.

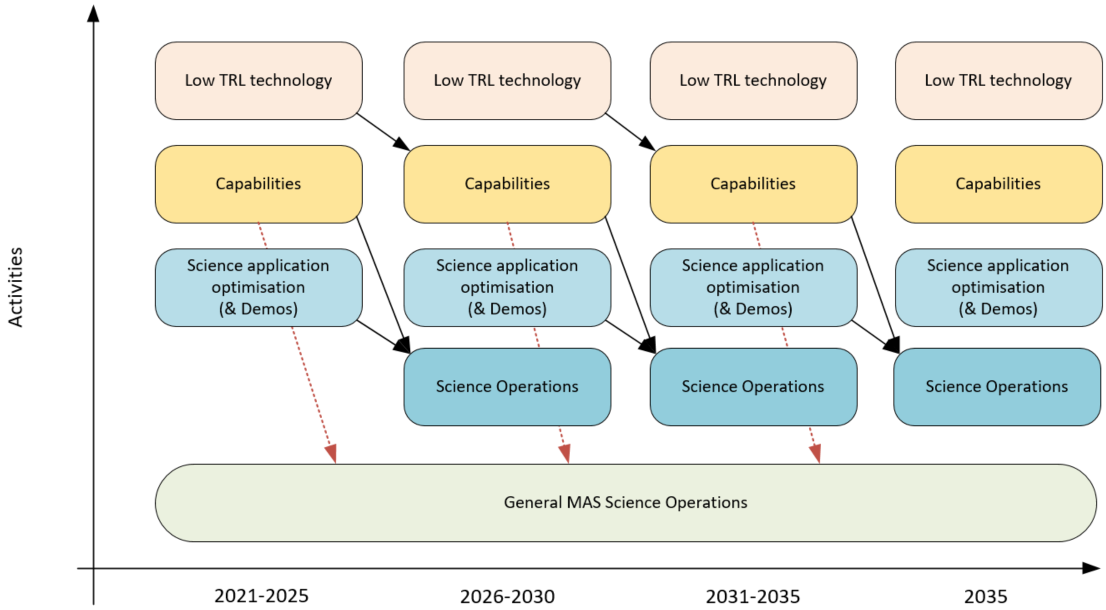

Figure 6. Proposed MAS development plans

The key to delivering the MAS science extension will be the formation of tightly integrated mixed science, engineering and data teams to address the specific application area. Each party would bring a different but critical perspective to the problem and hence would allow us to rapidly produce better solutions. Along with having the science community integrated into the individual MAS science extension activities, a combined science and technical team should review the technology developments that would enable other science activities to be moved from ship-based to MAS-based methodologies. These would then be folded into the five-year development plans.

The recommendations for the first phase of operations are outlined below.

5.2 Phase 1 – Short term plan 2021 – 2025

5.2.1 General recommendations

To be able to reduce the carbon cost of the current operations, we must understand how much CO_2 is actually being generated and from where. Thus, NMF should develop a calculator to estimate the carbon cost for the different operations in the marine programme. This should include logistics, personnel travel, and other ancillary activities. This would enable NMF to target changes that would maximise carbon savings, and thereby reduce CO_2 output in the short to medium term.

The upcoming LEO satellite revolution will significantly increase communication bandwidth to and from ships. This increased bandwidth will enable many current activities to be run from shore and aligns with the ROV virtual control room concept. NMF should aim to move these activities to shore-side operations, thereby reducing the number of staff aboard the vessels. These developments would align with the need to reduce the size of the ship's company associated with a move toward smaller renewably powered vessels.

5.2.2 Technology Pipeline

To build the next generation of marine robotics, we need a pipeline of ideas and early developments to turn into new capabilities. The technology pipeline will need to cover a wide range of topics, as highlighted by the NZOC Workshop 4 participants, and will include collaborative science and industrial research projects funded by Innovate UK, UKRI, DASA and the EU. One broad area to cover is risk and reliability for vehicles and sensors. Risk and reliability are intimately bound to all stages of the development and deployment lifecycle. Reliability should be bound in during vehicle creation, and once operational should be used in planning (risk modelling looking at vehicle fault analysis and operational conditions) through underway operation (identifying pre-fault conditions and biofouling) to post-deployment assessment (building reliability data to drive process improvements and better risk modelling). ROV developments are another broad area that should be monitored. This includes the use of shore-based control rooms for piloting ROVs and the associated virtual control room concept for scientist and public participation. Alongside this, we are seeing improved ROV human-machine interfaces to reduce the piloting load and the development of autonomous ROV behaviours, including for intervention tasks. These autonomous behaviours align with the ambition for hovering AUVs. Another broad topic to cover is the development of discrete new capabilities for marine robotics. Examples of these capabilities include buoyancy engines for the AUVs like ALRs, docking capabilities both USV based and fixed, and networking between vehicles and fixed infrastructure for vehicle coordination and data harvesting, amongst many more. Finally, we should continue to review what current ship-based science activities could conceivably be undertaken by marine robotics and what development work would be required to make the transition.

5.2.3 MAS capabilities developments

Over the next five years, the following marine robotic development would progress the transition to a low carbon ocean observing capability.

The “brains” of marine robots are critical to their ability to undertake more complex behaviours and thereby increase their capabilities. Hence, the NOC vehicle Onboard-Control-System (OCS) and shore side Command and Control (C2) systems will need to be further developed and extended beyond normal maintenance and upgrade. Specific areas of development include the Automated Piloting Framework (APF) of the C2, which allows machine-based control of the long-range fleet. The C2 will be further extended with integration of new platforms, development of a PI portal, creation of fleet planning tools and refinements of data flows. New autonomy behaviours will also need to be developed within the OCS to support safe under-ice operations. The OCS will be further extended with integration of new sensors, refinement of the backseat driver interface, and integration into new platform types. The OCS and C2 provide invisible infrastructure that is critical to effectively operate marine robots, and is becoming the key differentiator between systems.

Alongside the core OCS and C2 capabilities, the systems need to be easily extendable to support more niche processing. An example of this is sensor specific processing algorithms as raised by the NZOC Workshop 4 participants. These need to be run in real-time on the vehicle and could either send back processed data or could be used to guide the robot. Likewise, there are similar requirements for mission-specific processing algorithms integrated into the C2 infrastructure, which could be used for fleet planning, fault detection, data visualisation, etc. NMF staff will not be able to develop all of the niche campaign-specific algorithms required and so should enable third parties to develop software that easily integrates into the OCS and C2 architectures. The third-party developers will need access to the interface information on these systems. Thus, developer portals should be created that include descriptions of the interfaces, example code, and tips. This mix of core infrastructure and third-party algorithms will enable rapid enhancement of the capabilities of the robotics fleet, and the OCS and C2 will become core national infrastructure supporting marine science.

The existing marine robotics fleet should be upgraded with the addition of new capabilities, new sensors, and new vehicle types. Examples of the new capabilities include developing RAFOS sound source receivers for under-ice navigation, and producing a back seat driver capability for the glider fleet. The new sensors to integrate into the fleet include glider based passive acoustic monitoring systems, lab on chip sensors for the Slocum gliders, and particle measurement systems for the ALRs. Finally, new vehicle types need to be brought into the national marine equipment pool; these include the final commissioning of the A2KUI and ALR1500 vehicles. Additionally, as noted in Section 3.6, there is a need to operate near boundaries and on the seafloor, so work should be undertaken to further develop hover capable and crawling vehicles. These additions to the fleet would increase the range of science missions that marine robots can undertake and hence increase their use in observing the ocean.

5.2.4 Extending MAS Science Applications

Scientists, sensor & platform engineers, and data managers will need to work together to demonstrate new science applications for marine robots. The existing Oceanids sensor programmes have developed new sensors that enable new applications. These sensors have been integrated into the marine robotics fleet but have not been optimised for the vehicles or fully demonstrated. The vehicle and sensor combinations should be refined and used alongside ship-based methods to demonstrate the new capabilities.

The first new science area to be developed should focus on upper ocean biogeochemistry using the ALR and the Oceanids lab-on-chip sensors. These sensors should be refined to reduce power, thereby enhancing the range of the ALR. The sensor suite should also be augmented by including a particle imaging system to provide more information on the carbon cycle. The ALR and sensor suite could be usefully tested at the Porcupine Abyssal Plain (PAP) observatory to deliver real-world science to complement the existing PAP data streams.

A second science area that should be developed focuses on shore launched bathymetric and camera surveys using the ALR. This would involve integrating a low power side scan and camera systems such as the Oceanids BioCAM system into the ALR. The ALR should also be linked with a USV to provide a navigational aid and communication relay. This combination would enable low-cost surveys of the North Sea to assess the environmental impact of offshore renewables and would also allow cost-effective monitoring of decommissioned oil and gas infrastructure. Further to this, the system would also enable inexpensive surveys of marine protected areas such as Haig Fras and the Darwin Mounds. An ALR and USV combination would open up the majority of the UK's EEZ to shore launched high accuracy seabed surveys.

Finally, as noted in the Gap Analysis section, there is the potential to use marine robots to take the core measurements involved in hydrographic sections. The first phase of delivering on this potential is to review what is achievable using current vehicles and sensors. The performance of these can then be compared to the WOCE standard required for hydrographic sections, and a development roadmap can be created, e.g. by taking water samples to enable post-mission sensor calibration. Once the sensor and sampling system has been created, it should be trialled on an ALR as a surrogate platform to demonstrate the measurement performance. These trials should be run alongside existing ship-based science deployments to enable a comparison between the robotic and ship-based methods. Potential ship-based sections include the Jonsis line run from the Orkney Island, the Ellett line run from Scotland to Iceland, and the RAPID array running across the Atlantic.

Alongside the trials, a design should be created for a dedicated AUV which could undertake basin-scale hydrographic sections, e.g. for RAPID. The work outlined would build a solid foundation for using low carbon robotic platforms to routinely measure the core parameters needed for hydrographic sections.

Demonstrating these three different science capabilities will build confidence in the community in the quality of data that the systems produce. However, it is expected, as noted in the MAS Science optimisation, that dedicated funding will be required for routine use of the platforms after the initial proving phase. This will allow further optimisation of the robotic approach and will help the transition from the current ship-based protocols.

5.3 Long term plans post-2026

Marine robotic technology is moving quickly, so creating detailed plans for developments beyond the middle of the decade is tricky. But we can make some broad observations. We will continue to refine and enhance the OCS, C2 and data infrastructure. These enhancements will increase under-ice operational effectiveness and enable the development of light intervention capabilities for the hovering AUVs. Also, docking capabilities should have matured (as will have the platforms), and so developing docking capabilities for the NMEP fleet should occur in the latter half of the decade. We would look to build both fixed and mobile docking systems. The mobile docking systems would be attached to a USV, and so we would need to work with the manufacturer to develop a suitable system for our vehicles. When higher energy density solid-state batteries become available in the latter half of the decade, we would look to use these to power the glider and ALR fleet. This may not increase the range compared to primary batteries but would reduce cost and lower the carbon associated with each deployment. Finally, developments in other technology areas (e.g. sensors, autonomy, and commercial robotics) will guide the development of the fleet and may provide solutions to some of the hard problems identified around sampling and deployment & recovery of heavy infrastructure.

5.4 Key Challenges – Risk Management and Transition

As with any disruptive change, there is a mix of technical, cultural and structural challenges which need to be overcome. Most, but not all, of the technical challenges can be addressed in the next 15 years with a suitable investment of time and money. The exceptions are heavy infrastructure operation (e.g. ROVs, Seismics, Rock drills) and taking samples (e.g. sediment, biological and water). Operating heavy infrastructure is unlikely to move to robotic systems in the next 15 years and so should be assumed to continue on crewed vessels or not to be available. Likewise, the majority of samples taken will require a crewed vessel. However, it is expected that marine robots will take an increased portion of these samples in the next 15 years. This increase in robotic sampling will require considerable investment in sampling technology, as will be outlined in NZOC Work Package Report 5.

Alongside the technical challenges, the cultural change necessary will require significant engagement with the community. It was clear from NZOC Workshop 4 that the community had significant concerns over the capabilities of marine robots to provide the necessary scientific data. There are also structural barriers to using marine robots as most existing ship-based protocols are lower cost and higher quality than their MAS equivalent. Hence, the community only use marine robots when it offers a clear scientific benefit; the carbon cost is not factored into this calculation. Thus, to foster the transition to lower carbon observations, it is essential to provide ring-fenced funding for marine robotic missions to demonstrate the capabilities to the broader science community. These missions are likely to be more expensive than performing the same operation with a ship in the short term.

Transitioning to a lower carbon observing system is going to be extremely challenging and will require significant disruption to the status quo. The transition will require substantial investment and, in the short term, is likely to produce lower quality scientific data to the community.

5.5 Impact on Net Zero vs 'Do Nothing'

As highlighted in Section 4 on the carbon cost of operation, the main benefit of using marine robots is not from the “fuel” used but from their smaller size. Thus, they require less energy to manufacture and less energy to operate. Not moving as much of the in-situ measurement to low carbon systems will significantly curtail the scope of reducing the carbon of the existing observing system. Thus, the only way to reduce the carbon associated with the measurements will be to cut the capability.

Moving a substantial amount of oceanographic science from ships to marine robots will reduce, not remove, the carbon impact of collecting the data. However, the amount of reduction could be substantial. For example, using a Saildrone Surveyor to undertake a deep-water bathymetric survey would be roughly three orders of magnitude lower carbon than performing the same operation using a global-class research vessel. On the flip side, replacing a mooring array place by a renewably powered research vessel with a permanent long-range AUV presence could have a higher carbon cost especially if the AUVs utilise primary batteries. Thus, it is going to be important to make sure we fully understand the carbon cost of each operation, and as noted in Section 5.2.1, it will be essential to build detailed carbon costing models to calculate the cost for the science campaigns.

6 Implications for E, D & I

Moving scientists from seagoing vessels where they are intimately involved in collecting samples and producing data to simply watching computer screens where data is streamed from marine robots will significantly change their roles. The transition will open up new opportunities for people who either struggle to or can't go to sea, and it will provide equal access to any scientist with an internet connection. This easy access will open up the profession to a broader selection of society and would, for example, allow those with young families to see their children when a campaign is underway. However, much will be lost in the transition. The worries about what will be lost was expressed by the NZOC workshop 4 participants. The concerns included: a loss of connection with the work; reduced engagement with other disciplines and the cross-fertilisation of ideas; more difficulty in building strong working relationships across generations and disciplines; and a reduced enjoyment of the job. The move to using marine robotics will also change the skill sets required of a marine scientist. It will favour data analysis and software engineering in preference to more practical skills. Some current skills will also become redundant as they are automated, and a large portion of scientists will need retraining for this new paradigm. So, although there will be many winners from the transition, there will also be those currently in the profession who will lose out and will need to be supported and retrained.

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Appendix A. The carbon cost for different vehicles

NZOC Analysis of CO2 per km for different systems

Cell embodied carbon - secondary	150	kgCO2e/kWh
Cell embodied carbon - primary	150	kgCO2e/kWh
Grid carbon intensity	100	g/kWh
Charging efficiency	85%	
# of rechargeable missions	10	
Manufacturing CO2e	5	kgCO2e/Kg

	Manufacture		Battery		Range per mission	Expected life	Battery	Embodied Carbon vehicle	Embodied Carbon Battery	Embodied Carbon total	"Fuel" Carbon	Total Carbon	Total Carbon
Vehicle	Mass (kg)	kgCO2e	Energy (kWh)	kgco2e	km	km	kwh/km	kg/km	kg/km	kg/km	kg/km	kg/km	g CO2/km x kg
Glider - rechargeable	65	325	2.8	420	1800	30000	0.0016	0.0108	0.014	0.025	0.00018	0.0250	0.384867
ALR6000 - Rechargeable	600	3000	15	2250	940	30000	0.0160	0.1000	0.075	0.175	0.00188	0.1769	0.294796
ALR1500 - Rechargeable	780	3900	40	6000	2500	30000	0.0160	0.1300	0.200	0.330	0.00188	0.3319	0.425490
A2KUI	2000	10000	50	7500	300	30000	0.1667	0.3333	0.250	0.583	0.01961	0.6029	0.301471
Hugin Endurance	10000	50000	400	60000	2000	60000	0.2000	0.8333	1.000	1.833	0.02353	1.8569	0.185686
Waveglider (SV3)	155	775	2.7	405	6000	30000	0.0005	0.0258	0.014	0.039	0.00005	0.0394	0.254105
Autonaut (5m)	280	1400	4.3	645	6000	30000	0.0007	0.0467	0.022	0.068	0.00008	0.0683	0.243754
Saildrone - Explorer	750	3750	2	300	6000	30000	0.0003	0.1250	0.010	0.135	0.00004	0.1350	0.180052

	Manfuacture		Battery		Range per mission	Expected life	Battery	Embodied Carbon vehicle	Embodied Carbon Battery	Embodied Carbon total	"Fuel" Carbon	Total	Total Carbon
Vehicle	Mass (kg)	kgCO2e	Energy (kWh)	kgco2e	km	km	kwh/km	kg/km	kg/km	kg/km	kg/km	kg/km	g CO2/km x kg
Glider -primary	65	325	7.2	1080	4500	30000	0.0016	0.0108	0.000	0.011	0.24000	0.2508	3.858974
ALR6000 - Primary	600	3000	25	3750	1500	30000	0.0167	0.1000	0.000	0.100	2.50000	2.6000	4.333333
ALR1500 - Primary	780	3900	80	12000	4800	30000	0.0167	0.1300	0.000	0.130	2.50000	2.6300	3.371795

NZOC Analysis of CO2 per km for different systems

MGO CO2 emission	3.15
Life (years)	25
Typical distance travelled per year (km)	60000
Operational days	200
Distance per day (km)	300
Distance per day (NM)	161.987

	Manfuacture		Fuel		Distance km / day	Expected Life km	Battery	Embodied Carbon vehicle	Embodied Carbon Battery	Embodied Carbon total	"Fuel" Carbon	Total	Total Carbon
Vessel	**Mass**	**kgCO2e**	**Fuel per day**	**kgCO2e**			**kwh/km**	**kg/km**	**kg/km**	**kg/km**	**kg/km**	**kg/km**	**g CO2/km x kg**
James Cook	5401000	27005000	11000	34650	444.48	1500000	0	18.00333333	0	18.00333333	77.9562635	95.95959683	0.017767