Ethics of marine robots: report for the Net Zero Oceanographic Capability Project (NZOC), June 2021

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1. Introduction

This report, prepared for the National Oceanography Centre as part of the Net Zero Oceanographic Capability (NZOC) project, presents a summary of ethical issues identified concerning the development, use and impacts of robots (and other unmanned vehicles) in the marine environment. With a focus on research robots that might be developed or used by the UK research community, it also touches on some aspects of commercial or military applications, where they might cross-over with research applications.

The report is split into five sections, starting with this introduction. The second section summarises some of the key ethical issues currently existing in marine research, while the third section does the same for identified issues with AI technology; both sections set the context for more specific information in following sections. The fourth section is a mapping of ethical concerns about robots in the marine environment. This section is the result of a rapid review, involving scanning the available literature (both academic studies and grey literature). The rapid review was guided and informed by preliminary conversations with engaged specialists working with the NZOC project in the areas of future science need; policy and regulation; ship technologies; marine autonomous systems; and data ecosystems, as well as other experts working in the area of marine autonomous vehicle technology and regulation.

It is worth noting that the information summarised in sections two to four is a review of the literature around these topics and therefore represents a variety of ethical frames. The choice of ethical frame by the author of an original study will affect the outcome of any particular research or policy document, and thus these sections must be read precisely as summarising some of the ethical views shared on this topic so far.

Nonetheless, this mapping of ethical concerns should give some signals for the nature of ethical debates that have either already started or are to come when considering robots in the marine environment. Section five then considers methods for predicting and avoiding or reconciling ethical hazard in the area of marine robots. This section summarizes some of the ethical frameworks and frames and proposes several recommendations for NZOC in considering marine robot artefacts into the future.

2. Ethical issues in Marine research

2.1 Ethics in Marine Research / Oceanography

Understanding our oceans is key to a sustainable future and combating climate change (Visbeck, 2018). In some ways, the methods scientists use to study the seas have not changed in hundreds of years. Since the 1700s, researchers wishing to study the seas have chartered ships and sailed to new locations to take physical measurements and collect data. However, in the age of anthropogenic climate change, the need for learning more about our world must be balanced with the even more urgent need to reduce carbon emissions.

The scientific study of the ocean is central to ensuring it is protected and sustainably managed, but research comes with its own impacts. These impacts need to be considered, monitored and reflected upon within an ethical framework to ensure research is being as true as it can be to its ultimate objectives.

Oceanography is not unique in this respect but, compared to some fields of research such as medical studies, it is in the early stages of developing its ethical approach. This means it can learn from existing frameworks whilst addressing ethical issues that are specific to the field. Alongside this, innovation in data collection and analysis in marine research has provided new opportunities for the sharing of data and social benefits arising from research and there is a need to make sure these are being harnessed responsibly.

The ultimate aim for ethical marine research is to strike the balance of providing maximum benefit to science, society and environment whilst leaving a minimal negative footprint on the marine realm (Barbier, 2018)

2.2 Ethical issues and challenges

A number of ethical issues have been identified by the marine research community (see box 1). Some involve more direct environmental impacts, such as the effects of ocean observation on the seabed or the impact of noise, pollution and plastics on marine biodiversity. Others are more socially and economically embedded, such as the sharing of data or benefits resulting from research.

Box 1: Ethical issues arising in marine research

- Interactions of research processes with the environment and impacts on natural processes and phenomena, for example through animal tagging and disruption of seabed.
- Pollution impacts on biodiversity from plastics, noise, lost/disposable equipment and research vessels.
- Sustainability of research activities in terms of their use of energy and natural resources
- Issues of national sovereignty and ocean governance and different interpretations of what is and isn't allowed in terms of movement of research vessels and coastal management.
- Commercial or military applications potentially resulting from publicly funded research that impact local communities or global society.
- Sharing of data and social benefits resulting from research such as education, knowledge transfer and implementation of evidence-based recommendations.

END BOX

Most often marine research will face more than one ethical challenge. In addition marine research projects are increasing in their complexity and becoming more multi-disciplinary, multi-sector and multi-cultural (Barbier, 2018). This development could potentially make the ethical roadmap for marine research more difficult to navigate but, on the other hand, the involvement of multiple stakeholders and nations can provide a more robust backdrop to the development of ethics, helping to ensure diverse interests are represented and disciplinary and political blindspots are avoided.

Technology has enabled our capacity to collect and analyse large amounts of data, whilst advances in modelling are allowing marine researchers to make more detailed projections about the future state of the oceans. As models are often used to inform policy decisions, for example the setting of harvest limits based on maximum sustained yield, it is important they are developed responsibly and are transparent about the level of uncertainty involved (see box 2).

Box 2 – Ethical issues in modelling (Schlipp, 2010)
All models are built on assumptions, for example in fisheries population models it is assumed there are no immigrants or emigrants to a population besides births and deaths. These assumptions need to be transparently discussed. When a model becomes more complicated (through the addition of parameters) it becomes both more realistic but also more susceptible to error so the uncertainty may increase. This tradeoff must always be

considered, especially if there is a shift from single-species models in population dynamics to multispecies and ecosystem models.
END BOX

Some of these ethical challenges and the interplay between them have been brought to the fore by real-life examples of marine research that have encountered controversy. These provide valuable insight into ethical considerations for future research. For example, Marsh & Kenchington (2004) introduce their debate about the role of ethics in marine biology and ecology with a description of a large-scale experiment to assess the impact of line fishing in Australian Great Barrier Reef that encountered public hostility (see box 2).

Box 3 – Great Barrier Reef Marine Park – Effects of Line Fishing experiment
In 1996 a large-scale experiment planned to open and close reefs in the Great Barrier Reef Marine Park in a controlled way to allow scientists to measure the effects of different fishing regimes on certain fish populations and reef communities. It created controversy, with opponents proposing the environmental harm of the experiment would be equivalent to logging of old growth forests, whilst marine ecologists argued that these detriments were balanced by the knowledge that would be gained. As a result a report was published on environmental research ethics that recommended ethical issues should be incorporated into legislation and that management agencies use a research ethics committee to advise on ethics issues. In 1997 the Great Barrier Reef Research Ethics committee was formed, consisting of members from a range of backgrounds.
END BOX

Drawing on this example, Marsh & Kenchington suggest there has been a lack of ethical discourse in the research community because of the assumption that the relative benefits of marine research outweigh the potential short-term costs. This is evidenced by research they conducted on the instructions to authors and reviewers of journals that accept papers on experimental marine biology and ecology. This found that more than half the journals were silent on the issue of ethics and a quarter restricted their concern to animals. This demonstrates that blind spots can exist and explains why ethical discourse has tended to occur when controversies occur. Ideally, ethical discourse could be developed, discussed and guide behaviour before these situations arise.

2.3 Ethical principles and recommendations

Marsh and Kenchington’s analysis of journals was completed in 2004 so there have been some advancements in the intervening years. From our scanning of the literature, we have found little published academic debate on this subject so far. However, recent initiatives – such as the current call for papers from Frontiers journal on Ocean Science and Ethics and the work of the Institute for Science and Ethics – are now instigating these discussions.

The Institute for Science and Ethics promotes the use of a model of governance based on socio-ecological systems to make knowledge accessible to all. It has published ethical guidelines for ocean observation (Barbier et al., 2018), inspired by the charter on Access and Benefit Sharing produced by CIESM (an intergovernmental organisation promoting international research) and guided by the AlantOS H2020 project as an example of good ethical practice in marine research (see box 4). These guidelines are discussed below.

Box 4: AltantOS H2020 project
This project aims to enhance and optimise the integrated Atlantic Ocean observing systems and includes 62 partners from 18 countries. It aims to integrate current research activities in ocean observing and to provide information and products necessary to cope with global challenges such as climate change and pressures on natural resources. At its core is the concept of Responsible Research and Innovation (RRI).

END BOX

Open Access Data - Technological development has not only provided opportunities to collect more data but opportunities to share data more easily, for example the use of satellites to transmit oceanographic data in real-time. There are huge benefits in linking and sharing data: it can provide more powerful and comprehensive analyses, increase efficiency of data collection and avoid duplication. These benefits ensure that maximum societal and environmental benefit is gained from research, which potentially reduces the amount of individual research projects. In addition, the collaborations needed for data sharing are important for scientific progression. A good example of this is the Argo Data System (see box 5) which provides open access to the data collected by robotic observation instruments. For initiatives like this to reach their potential of real-time, open access there must be thorough integration of data though the development of interoperability criteria and standardisation of best practices with data access and storage.

Box 5– Argo

Argo is an international program that collects information from inside the ocean using a fleet of robotic instruments that move up and down between the surface and a mid-water level. Each instrument (float) spends almost all its life below the surface. The data that Argo collects describes the temperature and salinity of the water and some floats measure properties to describe the biology/chemistry of the ocean. The float measurements are sent to regional data centres where they are given rigorous quality checks and then passed to two global data centres from where they can be accessed by anyone wishing to use them. https://argo.ucsd.edu/about/

END BOX

Sustainable data collection - For marine research to be sustainable, the collection of data must be efficient. Sharing existing infrastructure and facilities for ocean observation prevents duplication of effort, minimises investments and reduces costs. The AtlantOS H2020 project (see box 4) has established interfaces between observation networks, whilst other collaborations share infrastructure such as PIRATA (Predictive and Research Moored Array in Tropical Atlantic – see box 6) which integrates supplementary sensors on its buoys to support additional research.

Ethical knowledge sharing - Alongside the sharing of data and information there is an ethical drive to communicate the knowledge from marine research to policy makers and the public. This can mean building a communication element into marine research projects and a training element to ensure capacity building so researchers are able to apply ethical guidelines to communication. Some programmes, such as PIRATA and POGO (Partnership for Observation of the Global Ocean) offer seats for students to experience the working atmosphere with the aim of developing ethical awareness in researchers from an early stage in their career. It has been suggested that scientific ethics should be taught as part of studying oceanography where teaching is not just presenting facts about the marine world but also an introduction into the way we make use of scientific knowledge (Tomczak, 2004).

Communication is key to ethical research and the communication itself must also be ethically bound. Erickson et al. (2019) discuss the need for professional ethical guidelines for marine conservation communication, and this can be extended to the communication of marine research that informs conservation.

Box 6 – PIRATA (Prediction and Research Moored Array in the Tropical Atlantic)

PIRATA is an international observing network to improve both knowledge and understanding of the ocean-atmosphere system in the tropical Atlantic Ocean. Launched in the framework of the international program CLIVAR (CLImate VARiability and predictability), PIRATA

operates by an array of moored buoys supported financially, technically and logistically by France, Brazil and the USA http://pirata.ccst.inpe.br/en/about-pirata/
END BOX

Managing environmental impacts - Unfortunately observation, monitoring and testing in the marine environment also has the potential to disrupt the ecosystem. This can be through noise pollution from sonar systems and seismic testing, or from waste pollution from devices or instruments that have reached the end of life or been lost. In cases where the research itself is assessing an impact on the environment it may need to employ an intervention that by design will affect the environment, such as the Great Barrier Reef experiment (see box 2). Ethical choices can be made in terms of how the equipment is manufactured, the use of new battery technology with lower risk of impacts, the use of marine vibrators instead of air guns and appropriate recycling activities. These choices can be encouraged by a combination of regulations and financial incentives.

Ensuring ecosystem welfare - Since marine animals are resources for many coastal communities (e.g. fisheries and tourism) research has an ethical obligation to apply its knowledge to manage these resources sustainably. As such, ethical challenges include balancing obligations to animal welfare and obligations to a broad group of stakeholders. There are also ethical issues in the dissemination of data and impact on animals, for example now that data is so quickly available, the implications of this must be considered in terms of providing location information on endangered species or stocks/populations of commercial interest.

Governance, equity and fair benefit sharing - Zones and boundaries within the marine environment are as important as they are on land, if less visible. Regulations and laws to govern access to and utilisation of ocean resources must also be applied for research purposes. UNCLOS defines coastal jurisdictions and there are other regional conventions that should be respected to ensure ethical behaviour. It is important for researchers to familiarise themselves with these and for institutions to provide support to researchers to understand them, especially where there are disparities between interpretations.

Alongside recognition and respect of geographic boundaries and zones, there is a need to recognise geographic disparities and inequalities. Many countries do not have the resources to conduct marine research and yet researchers from other countries are able to study their marine environment. To help establish shared ownership of research, it is important to consult with local scientists and stakeholders and this should be done prior to designing new projects. One way to do this is via a co-design approach where local researchers and stakeholders are involved in the actual research design. A good example is the PIRATA network (see box 6) which involves collaboration between France, Brazil and the USA.

3. Ethical issues in AI and robotics

The rapid and continuing development of AI brings with it many ethical quandaries, some of which are currently being addressed and others of which are more complex and do not have an obvious or immediate solution.

As the field expands beyond its current implementations and into ever wide-ranging aspects, there is a need to inspect the ethical implications of current and future applications. This is the foundation for creating a set of ethical standards for AI and robotics, which are beginning to emerge in nations across the globe.

Here, we will summarise what these major ethical questions are and why they are important. Where does human responsibility for AI start and where does it end? How will an increasingly technology-driven world influence energy use and broader concerns for the natural environment? And how can we ensure that access to these new technologies is equitably distributed across the globe and within societies?

3.1 Impact on human agency

One of the most immediate concerns around AI is the design of robots or other intelligent machines that generate behaviour outside of what was expected by the programmer. This concept has been often fictionalised, such as in the film *Ex Machina*, in which a humanoid robot develops self-awareness to the detriment of its creator – a theme which extends back to Mary Shelley's *Frankenstein*.

In its most extreme form, this concept is known as **'superintelligence'** or 'the singularity', a point in time at which AI becomes so sophisticated that it exceeds human intelligence, such that the AI itself could design a machine of even greater abilities, eventually leading to the extinction of the human race.

As unlikely as such a scenario may be, the question of who is ultimately **responsible** for AI is an important one. If an AI acts in an unexpected manner or generates unintended consequences, who should be held accountable for it? Is it the original developer of the AI, the manufacturer, the operator, or the owner? Can an AI itself be held responsible for its actions? The obvious answer might appear to be the original developer, the person or people who wrote the code, but as many machine learning algorithms can learn and adapt on the basis of new data, can a developer be held responsible for an action they did not program?

There is currently no universal standard for responsibility when it comes to AI. According to the European Parliament Resolution on AI (2017), legal responsibility always lies with a human actor, such as the developer, manufacturer or operator. Self-driving cars for example would be the responsibility of the owner. However, not all types of AI are the same, nor are their applications, and there remain many unanswered questions when it comes to responsibility.

One possible way to avoid unintended consequences is keeping a **'human-in-the-loop'**. In other words, having a human operator available to supervise a robot or automated process. An example of this is having a human user to annotate data or validate models in a machine learning workflow. In human-in-the-loop systems, humans work *with* the technology to supervise its learning and actions.

One area where the idea of having a human-in-the-loop is particularly important is that of autonomous weapons, weapons which can 'search, identify, select and attack targets without real-time control by a human operator' (European Parliament, 2013). Although some have argued that a human-out-of-the-loop approach could propel progress in the field, the idea that any AI should be able to take a human life is uncomfortable for many and groups around the world continue to campaign against lethal autonomous weapons. EU MEPs recently voted in favour of a report stating that AI must be subject to **human control** so that humans can disable unforeseen behaviour, with a strategy banning lethal autonomous weapons on the way (European Parliament, 2021).

Another way to mitigate the risk of unforeseen behaviour in AI is to improve **transparency**. This means publicising what an algorithm is doing, what data it has been trained on, and ideally making the code open source. Improving transparency helps users and those impacted by AI to understand how and why a decision has been made. AI systems that produce explanations of their decisions and behaviours are known as **explainable systems**.

Transparency of this type not only engenders trust in AI but could also help to identify cases where an AI might be biased or even dangerous. However, this is not always possible. Some deep learning systems cannot be easily interrogated; decision making in so-called **'black box AI'** systems cannot be traced, even by the original developer. In these cases, it may be important to consider the stakes of the decision at hand. If the decision is high stakes, transparency may be more important and therefore the use of black-box AI might be inappropriate. This remains a topic for debate; some commentators argue that not all human decisions can be explained and that black-box AI can be more accurate than more explainable alternatives.

3.2 Impact on society

As AI becomes able to perform a wider range of tasks performed by humans, and even some tasks a human would not be able to perform, what does this mean for the **job market**?

This may appear to be a new concern but in fact people have been worried about the loss of jobs due to technology for centuries. In the 18th Century, fears about technological unemployment peaked with the Industrial Revolution, but these fears existed even in ancient societies. Aristotle spoke of a 'shuttle [that] would weave' without a human hand, indicating that if machines became advanced enough to perform human activities there would be no further need for human labour (Campa, 2014).

In the era of AI, technology is playing a role in progressively widespread areas of life, putting not only manufacturing and hands-on jobs at risk but also 'white collar' jobs such as translation, secretarial work, administration and basic care work. One study in the U.S. (Frey and Osborne, 2013) suggested that almost half of workers are likely to see their jobs automated over the next 20 years. Following the COVID-19 pandemic, there are already reports of AI and robots replacing some of the millions of jobs lost (Kelly, 2020; Samuels, 2020). In summary, although it is likely that AI technologies may generate significant **unemployment** in the short term, in the long term it may lead to the creation of jobs.

There are also **equality** concerns related to changes in employment, as the higher-level professions that require more education are less likely to be impacted by AI than those that require less education. Younger people in the first generation to work alongside AI may also be disproportionally affected.

It is also important to consider whether and how **access to AI** might be shared equally, and not held only by those who have the most power or financial resources, such as wealthy nations and large technology companies. One idea to prevent this is to position AI not as a private good, but for the benefit of all. Other ways to prevent deepening inequalities include retraining programmes, economic policies such as universal basic income, and other forms of social and financial support for displaced workers.

Another type of inequality that might be created or perpetuated by AI is **bias** against certain sections of society. This can occur because of bias in the data used to train machine learning models or unintended social bias in the design of the algorithm, which is then reinforced by the AI.

As well as large databases, some of the data used to train AI comes more directly from people's behaviour. For example, Intelligent Personal Assistants (IPAs such as Amazon

Echo and Google Home) use direct interactions with the AI to learn and improve performance. In an ocean science context, AI that tracked the movements of fishing boats would actually be tracking human decisions and behaviour. The fact that this type of data may be collected and stored generates **privacy** concerns for many. A survey of owners of IPAs identified concerns about the devices collecting personal information and recording private conversations (Manikonda et al, 2018).

3.3 Impact on the environment

Although there are concerns about unintended negative consequences, many AI solutions are ultimately designed to improve life for humanity – but might this come a cost for planet?

The primary environmental concern related to AI is that of **energy use**. AI is run on hardware and requires significant and increasing amounts of power. Since 2012, the computational resources used in the largest AI training runs has doubled every 3.4 months – increasing by 300,000 times between 2012 and 2018 (AI and Compute, 2021). This has significant implications for carbon emissions; training a natural language processing AI for one year was shown to have a carbon footprint more than seven times that of the average human being (Strubell et al., 2019).

The hardware used to run AI must also be built and this too requires energy and precious **natural resources,** including rare earth metals. These metals are found in very small concentrations and are difficult to mine, separate and purify. Mining of more common resources, such as the nickel, cobalt and graphite used in lithium-ion batteries, is also damaging to the environment.

At the end of their life, electronics are often discarded and usually can't be recycled. This leads to a build-up of heavy metals and other toxic materials in the environment, which can degrade the quality of air, water and soil. **Electronic waste** or 'e-waste' is increasing as technology development accelerates. According to the UN (Forti et al., 2020), 54 million tonnes of e-waste was generated in 2019, equivalent to 7.3 kilograms for every person on Earth. It is a concern that AI will increase the production of technology, such as robots, making this problem even worse.

However, it is also possible that **AI could benefit the natural environment**. On a general level, AI could be used to modernise the energy grid to create a 'smart grid', better regulating supply and demand and allowing energy consumers to more accurately monitor their energy use, potentially reducing it. Google is reportedly already using AI to reduce energy consumption in its data centres (Middleton, 2018), a trend which should continue to develop for other data ecosystems. AI has also been applied to identify new combinations of materials that might replace rare earth metals, reducing the pressure on these precious natural resources (Dan et al., 2020). Furthermore, autonomous vehicles could help to reduce carbon emissions not only because of their more renewable fuel sources, but also because they can be programmed to follow efficiency principles and reduce journeys and congestion involving other vehicles.

Box: How UUVs are used
Unmanned underwater vehicles (UUVs) are submersible vehicles that are able to operate underwater without a human occupant. These can be either remotely operated or operate autonomously; either type can be considered 'robots'. While many UUVs now assist with deep and remote sea exploration, mining, wreck inspection and scientific research, they have primarily been used across nine different categories of military need (Button et al., 2009). This includes everything from harbour monitoring to mapping to meteorology:

Intelligence, surveillance and reconnaissance (ISR)	Mine countermeasures (MCM)	Anti-submarine warfare (ASW)
Inspection / identification	Oceanography	Communications / Navigation Network Node (CN3)
Payload delivery	Information operations	Time-critical strike (TCS)

END BOX

4. Robots in the marine environment: a mapping of ethical concerns

To follow is a section which maps some of the key ethical concerns, specifically regarding robots in the marine environment. The research and information synthesised here is the result of scanning and rapid review of the available literature, as well as conversations with engaged specialists to inform the possible futures for robots in the marine environment. These findings are necessarily indications, since we do not know for sure how developments with marine robots are going to evolve, and there are also some key limitations and challenges for some of the expected pathways (e.g. energy infrastructure development enabling a large uptick in numbers of UUVs).

As with the first two sections, the research synthesised here will express a variety of ethical frames, according to the viewpoint of the original authors – an aspect that is discussed and examined in more detail in Chapter 5. Nonetheless, this mapping of ethical concerns should give some signals for the nature of ethical debates that have either already started or are to come when considering robots in the marine environment.

4.1 The ethics of responsibility involving marine robots

A framework for responsible AI may include elements such as transparency, fairness, consistency with human values, and responsibility itself (Clarke, 2019; Dignum, 2017). In this context, responsibility means clarifying who is accountable for the outcomes of an AI, including potential unforeseen or adverse consequences. Central to this is the extent of human involvement in the AI, which includes not only the programming and development of the AI but also its operation.

4.1.1 Command and control of robotic marine vehicles

Unmanned underwater vehicles (UUVs) can perform a range of activities, from exploration and monitoring to search and rescue activities, in a largely autonomous manner. However, most UUVs still require some level of command and control by a human operator.

In a military context, command and control systems aim to 'achieve the established goals (fulfill the mission) […] by means of the exercising of authority by a specifically designated command over the resources/forces assigned.' (Delgado Gamella, 2020).

Where UUVs are the resources/forces assigned, the question is – who is the 'authority'? Who issues and is responsible for the 'command' issued to the UUV? This could be a diver accompanying the UUV, a remote operator or, in a more autonomous UUV, the person(s) who wrote the algorithm underlying its operation. These are to date formally unanswered questions. Although there are well-established legal liabilities for the operation of manned marine vehicles, legal frameworks are still being developed for UUVs and other autonomous and unmanned vehicles, both nationally and internationally (Lloyds Register Group, 2017).

The level of command and control exerted by a human operator also vary depending on the type of UUV. Some UUVs have a greater ability to respond to external conditions, and therefore greater autonomy, than others.

Floats, such as those deployed by the Argo program to collect data on the temperature, salinity and pressure of the ocean (Argo, n.d.), are otherwise unresponsive to the environment and cannot be controlled by a human operator. Data collected is sent to regional data centres via satellite and when their batteries become exhausted, Argo floats sink to the seabed and generally are not recovered. In this context, human control of the UUV is extremely limited and restricted to the phase of development before the UUV is sent into operation, and to quality control of the data received.

Gliders, which can provide data over long distances in ocean sampling research, have slightly more awareness of the environment surrounding them. An altimeter allows gliders to rise and fall appropriately and avoid hitting the seabed (Sherman et al., 2001). They are generally not able to detect more complex objects in the environment however, and so human control may be required to change the direction of the glider. However, more sophisticated unmanned gliders are under development, enabling greater autonomy. A 2019 study, for example, described the development of an unmanned underwater glider equipped with mechanical scanning sonar to map the below-water shape of icebergs, whilst remaining at a suitable distance to avoid damage (Zhou et al., 2019).

As well as the extent of human control being exerted, it is also important to consider the potential consequences of that control. In the UUVs described so far, the consequences are limited in scope, as the UUVs are inert and designed for the purposes of monitoring. However, if the application is military, or could be subsequently used for military uses, and the UUV has the potential to cause harm, the ethical implications of human control become more pressing (discussed further in the following section).

4.1.2 Human-in-the-loop vs human-out-of-the-loop systems

Although UUVs and other unmanned marine vehicles eliminate need for a human operator to manually steer and navigate the vehicle (as would be the case for a traditional underwater vehicle), many UUVs still require supervisory control from a human for monitoring purposes, and intervention if necessary (Ho et al., 2011).

This would be described as a 'human-in-the-loop' AI system. Human-in-the-loop systems have a human operator available to supervise an automated process, providing input at key stages, and are an important way to maintain human responsibility for an automated process (see section 3 for an introduction to human-in-the-loop systems).

One way of keeping a human operator 'in-the-loop' with a UUV is physically – using a sensor-containing umbilical cable between the UUV and a nearby ship to enable remote communication and operation. However, the use of an umbilical cable limits the depth the UUV can reach and requires a boat, which may also prohibit use in very shallow water, amongst other challenges (Azis et al., 2012). This type of control is therefore impractical for large distances and rarely used in truly autonomous UUVs. 'Hybrid UUVs' however may use an umbilical cable for some portion of the mission, for example near to oil station bases or wind turbines. One such hybrid, the Mesobot, is designed to track and study swimming animals and is initially powered and controlled by a tether attached to a ship but operates without human control while underwater (Keller, 2019).

A more practical human-in-the-loop system might include having a human operator located remotely from the UUV, to monitor the data received by satellite and intervene in a course of action if necessary. Current research in unmanned gliders for example (Anderlini et al., 2019) aims to use AI to optimise the performance of gliders before missions begin by recommending trim and flight parameters, saving pilots precious time before the start of the mission. However, the pilot remains ‘in the loop’ and is able to assess the results and change the settings if necessary. This is similar to a ‘human-on-the-loop’ design (Barnett, 2020), whereby a human operative would oversee the operation of the automated system, but the system would not by default require any human approval for its actions.

At the present time, human operators are frequently kept in the loop when using UUVs in order to make the high-level decisions the algorithm cannot (Petillot et al., 2019). Thus, rather than entirely replacing the human operator, automation is most often used to reduce or streamline human workload. However, as technology advances, it is important to consider what might happen when human beings are routinely no longer needed for a UUV to run. This describes the ‘human-out-of-the-loop’ approach, in which an AI is truly autonomous and capable of performing all of its functions without any human input or control.

There are of course technical challenges to achieving a fully autonomous underwater vehicle, the high pressure and currents of marine environments for one, but there are also important ethical implications of not having a human to intervene in the case of unforeseen consequences or to make the final decision after receiving a cue from the UUV.

This issue is particularly important in the context of military applications, such as autonomous weapons, where a lack of human supervision or control could have implications for human life. As many of the applications of UUVs are also military-based, these are important considerations for the UUV field. The EU stance on AI for military applications is that AI should not replace human decision making. “AI must always remain a tool used only to assist decision-making or help when taking action. It must never replace or relieve humans of their responsibility,” said Gilles Lebreton on the launch of the EU guidelines for military and non-military use of AI (European Parliament, 2021). In research applications, the lack of human supervision could also have implications for non-human life: depending on ethical standpoint, the same stance and guidelines could apply in this context (see section 4.4 on environmental disruption).

Algorithm transparency – making the actions of an AI algorithm human readable – is considered important in human-out-of-the-loop systems, but also when a human is in-the-loop. For example, a UUV could submit an action to the human operator with a justification, allowing the operator to understand why the suggestion has been made and make an informed decision on whether to accept or reject the action.

The Guardian AI system for autonomous vessels for example, which uses real-time data to make decisions on course, speed, and direction in UUVs, states that their AI is explainable: “every decision is transparent, auditable and able to be interrogated.” (Marine AI Ltd, 2020). Similarly, the Defense Advanced Research Projects Agency (DARPA) in the U.S. has developed an ‘Explainable Question Answering System (EQUAS)’ for its AI applications, which shows users which data was used in the AI’s decision making and can ask the system questions about recommendations (Raytheon, 2018; Wilson, 2019). This is in opposition to so-called ‘black box’ AI systems, which do not offer explanations of their actions.

BOX: Responsible code

Another way to think about responsibility in AI is in terms of the codebase – who wrote the code and whose responsibility they are under, for example, a public research body or a private company.

Whether the individual or individuals who wrote the code are responsible for its outcomes is still a topic for debate. While the Volkswagen emissions scandal was a clear-cut case of unethical programming, and saw engineers sentenced to prison time for their role in the debacle (White, 2017), a new legal category may be required for AI and autonomous robots, which can learn and develop actions not programmed or even intended by the original developer.

The level of human input at the development level can vary, which is important when considering responsibility. For example, a human operator who provides training data to a machine learning model is unlikely to be considered responsible for its outputs, whereas the lead developer on a project might be (Stephens, 2019).

There are also instances of AI itself writing code and creating its own outputs (Knight, 2021), complicating the situation further. In the UK, Parliament created a category of "computer-generated works" in the Copyright Designs and Patents Act of 1988 to protect works generated by a computer in circumstances where there is no human author (Stephens, 2019).

In terms of legal responsibility though, the picture is less clear. The UK government says "it is possible to foresee a scenario where AI systems may malfunction, underperform or otherwise make erroneous decisions which cause harm…[such as] when an algorithm learns and evolves of its own accord" and that new mechanisms for legal liability may be necessary for such situations (UK Parliament, 2018).

It is also important that the way that AI algorithms are coded is ethical and socially responsible. Both Google and Microsoft have published a set of recommended practices and principles for responsible AI, and PwC have developed an 'AI Toolkit' including frameworks, tools and processes to help companies to ensure their AI development is responsible, with key checks on accountability, explainability, fairness, security and regulation (PwC, 2019). Similarly, TensorFlow, which was developed by Google and is now one of the most popular machine-learning libraries, has released a series of resources to help developers integrate responsible practices into their AI algorithms (TensorFlow, n.d.).

END BOX

4.1.3 Data storage for UUVs

Many of the applications of UUVs are focused around the collection of novel data, including environmental monitoring, deep sea research and intelligence gathering. It is therefore important to consider where the collected data will be stored and accessed. Although the issues of data storage and access for UUVs are different to those concerning personal data, there is some overlap between the two.

One of the key concerns in both cases is who might access the data. In the context of a UUV, there are multiple options for data storage: on the UUV itself, on a nearby ship, on a server farm, or in a research centre. It is important to consider who might be able to access the data at each of these sites, and what their intentions might be.

Although much data on ocean monitoring is open access (e.g., the Argo project), some data collected by UUVs may be more important to protect, particularly from a national security perspective/in military applications.

If the data could be intercepted and used for nefarious purposes, security is key, and there are important trade-offs to consider here. Local storage may be in some ways more secure as it is accessible from the device only and therefore could not be accessed remotely by a hacker. Network Attached Storage (NAS) devices that are optimised for size, weight and power and support data encryption have been suggested as a secure solution to reduce the risk of data being accessed by unintended parties (South-worth, 2018). However, local-only storage may be impractical for many UUVs as it depends on their safe retrieval and prevents real-time data collection.

Remote storage, such as on a server or in a research centre, overcomes these problems and is frequently used for marine research purposes. However, it has been suggested that moving data between datacentres, as occurs in cloud computing, is unsuitable for sensitive, including militarily sensitive, data (de Bruin and Floridi, 2017).

However the data is stored, encryption is important to prevent sensitive data or code being accessed by unintended audiences. Encryption may be particularly important on a local device as, without it, if the UUV was captured the software could be modified, potentially enabling the UUV to be reverse-engineered and used for other purposes (South-worth, 2018).

After the data is collected, how it is used also has ethical dimensions. If the data collected by a UUV is to be used to make decisions, there is an argument that this data should be transparent, so the decisions made are explainable to the people they affect. Furthermore, if the research has been funded by the public, there is an argument that the data should be in some form open access (Baird and Schuller, 2020).

Indeed, in the UK, public funded research needs to make its findings open access and many other funding bodies will only support research that is to be made open access (UKRI, 2021). The European Commission has also encouraged its Member States to make public funded research results publicly available (European Commission, 2012).

However, making data and research findings open access means just that – that they can be accessed by anyone, which raises further questions regarding how the data is used from that point on.

4.2 The ethics of commercial or military applications from public funded marine robots

By making research findings freely available to everyone, open access is intended to democratise science and improve public understanding of science (Day et al., 2020). Open access also promotes transparency, collaboration and accountability, some of the key tenets of responsible AI.

However, it also makes it possible that technology developed and findings made by public-funded UUVs could be used by commercial entities for profit. In fact, it has been argued that open science ultimately contributes to the commercialisation of science (Fernández Pinto, 2020). Indeed, many programs and policy documents advocating for open science see commercial ventures as a desirable outcome from open access science. For example, the Panton Principles for Open Data in Science strongly discourage the use of licences which limit commercial re-use (Murray-Rust et al., 2010).

The commercialisation of publicly funded research has the clear ethical concern that private companies eventually profit from public money. It has also been argued that publicly funded research 'does the hard work', allowing commercial entities to come in later in the process and profit from this work. There is an additional concern that when public funded research is used for private profit, it does so without addressing the concerns that have been associated with privately funded science, such as insufficient focus on transparency, democracy and accountability (Fernández Pinto, 2020).

A related issue is the growing pressure on universities and research centres to bring in money, and therefore to commercialise their research outputs (Andalo, 2011). There may be financial incentives for research centres to patent and sell their technologies to private companies, who may use the technology in a way not originally intended. The pressure to develop research that can be commercialised may also lead to the prioritisation of certain types of research over others that are less likely to be monetised, which may compromise social responsibility goals.

These concerns are also related to the idea of fair benefit sharing (discussed further in section 4.5), as the commercialisation of UUV technology by large companies may lead to the disproportionate accumulation of profit and power.

4.2.1 Military use

There is also the possibility that publicly funded UUV technology could be used for military purposes, even if they were not so intended. The military applications of UUVs include autonomous submarines, vehicles for the identification and clearance of underwater mines, autonomous weapons, and vehicles designed to gather intelligence (Button et al., 2009).

Although a significant proportion of public funds are spent on military applications, they are acknowledged as such. There is however an ethical concern around public money being used for military purposes without that being its original intention.

Technologies that can be used for both military and civilian purposes are often referred to as 'dual use' (Perani, 1997). There is a concern that private entities may profit from these 'dual use' technologies; using government-funded science to develop military applications, resulting in further public spending. One study of OECD countries found that government-funded defense research results in significant increases in private sector research – on average, a 10% increase in government funded R&D in the defense sector generates a 5 – 6% 'spill over' increase in private sector R&D (Moretti et al., 2020a). The authors suggest that national differences in defence R&D spending help to explain differences in private R&D investment and the productivity of the private sector.

While this study suggests a spill-over effect from public research to the private sector, a recent report suggests that the private sector may in fact be driving research in this area. The report, which discusses autonomous agents for warfare in Europe, suggests that AI technology is developing with the commercial sector "in the driving seat". The report cites evidence that several large companies are funding the creation of start-up incubators to translate the results of publicly funded AI research into commercial applications (Marischka, 2020).

It has also been argued, however, that collaboration between public and private sector research (especially defense research) is a critical source of innovation. For example, jet engines, computers, radar, nuclear power, semiconductors, GPS and the Internet have all benefited from government-funded research (Moretti et al., 2020b).

4.3 The ethics of marine pollution from marine robots

Existing unmanned underwater vehicles (UUVs) can be broadly categorised by their operational location (underwater, semi-submersible and surface), form of control (autonomous and remotely operated) and intended function (combat, reconnaissance and rescue) (Bremer et al. 2007). While some UUVs drift or glide in the ocean and move with ocean currents, some use batteries (either single-use or rechargeable), others require diesel or gasoline fuel for propulsion, introducing a potential ethical concern around how these vehicles will pollute the marine environment.

4.3.1 Pollution, propulsion and the role of the naval architect

Knowledge of the scale, scope and impact of pollution from marine robots remains unclear, and this risk could be balanced with the potential benefit that a UUV's activities will provide. For example, if a UUV's scientific observations enable a better understanding of our carbon cycle and insight into how to combat ongoing climate change, is a certain amount of pollution an acceptable compromise?

According to Nichols et al. (2021), the introduction of carbon taxes, the rising cost of fossil fuels, and environmental regulation are pushing UUV manufacturers and naval architects to seek new and disruptive technologies that can meet required carbon emissions targets and keep UUVs cost-effective. Marine engine design now draws from innovation such as selective catalytic reduction systems, waste technology, gas recirculation, and more, and crafts are exploring the possibility of using biofuels, nuclear power, and innovative battery technology. In terms of propulsion, UUVs could investigate the use of hybrid propulsion systems, innovative hull design (including appendages and coatings), and energy saving devices to further reduce their carbon and pollutant footprints (Nichols et al., 2021). Overall, Nichols et al. highlight the important role of the naval architect in "[working] with natural scientists, such as marine biologists, in order to design vessels that work with nature to minimise the impact on the natural world".

Hoy (2004) highlights the potential of UUVs to incorporate architectures with "less potential for harm than other platforms", noting that the lack of crew also reduces the amount of waste or refuse emitted into surrounding waters. However, there is concern over how such vehicles may introduce either inorganic or engineered organic materials into natural environments. This concern rises considering that some engineered materials — such as biofilms or biomimicking robots, say van Wynsberghe and Donhauser (2018) — are able to alter form or functionality without human input, resulting in unpredictability. This suggests that, while we may be aware of what we are introducing into the marine environment now, we may be unaware of the longer-term consequences as materials become modified and integrated into the ocean.

Possible pull-quote: "There is no green robotics movement…we should push for this to be developed." – Sullins, 2011.

4.3.2 Lost vehicles

Pollution is not just a concern in terms of robotic components and fuel, but entire robotic instruments themselves. Unmanned marine vehicles have been introduced to marine environments on longer-term time periods, for example, in the form of Argo floats, which move with ocean currents and hover just beneath the sea surface throughout their 3-6-year lifetimes as they monitor and log sea parameters. According to the Argo Program Office (n.d.) at UC San Diego, USA, Argo floats are launched without the intention of recovery due to the resources required to find and recover them; instead, the floats fail when their batteries are exhausted, and drift until they leak and sink to the ocean floor, with only a tiny proportion reaching shore to be recovered.

Each year, floats that fail add material to the ocean: 90kg of copper, 45kg of zinc, 180kg of lithium, 180kg of lead, 17 tons of aluminium, 1.8 tons of plastic, 9kg of the chemical tributyl tin oxide (TBTO – required for salinity measurements), and – at most – 2 tons of garbage annually. The Argo Program Office (n.d.) states that these figures are “infinitesimal” compared to the existing natural and anthropogenic fluxes of these substances in the ocean, and highlights that Argo floats are generally widely distributed, lowering the risk of large and potentially harmful concentrations of marine robotic litter accumulating in one location. Argo floats represent a comparatively cost-effective and non-invasive way to observe the subsurface global ocean. However, due to the substances they release into the marine environment, there is a need for continued innovation in float technology to capitalise on recent advances in platform and sensor technologies (Roemmich et al., 2019) to, among other scientific benefits, minimise environmental impact.

Alongside Argo floats, autonomous gliders and drifters sometimes do not return, becoming damaged or caught at depth. Such equipment contains long-lasting components such as lithium batteries, effectively adding these to the accumulating anthropogenic waste in the ocean.

4.3.3 Plastic pollution

Plastic pollution is “a severe anthropogenic issue in the coastal and marine ecosystems across the world”, and mounting quantities of plastic contaminants can disrupt the structure, function, services and value of ecosystems across the globe, causing ecological impact at individual, community, and ecosystem scales (Thushari and Senevirathna, 2020). Plastic that finds its way into the ocean subsequently becomes eroded and degrades into smaller and smaller particles, eventually reaching the micro- and nano-scales. Particles that measure five millimetres across or less are known as microplastics, and are known to pose a threat to ocean and aquatic life. However, the precise impacts of microplastics — and their smaller fragments, nanoplastics — on our ecosystems, environment and human health remain unclear, with signs that these tiny pollutants are finding their way into the human food chain as they are consumed, and accumulate within, marine animals at different trophic levels — from zooplankton to turtles to seabirds (Setälä, 2018). As the scope and scale of the risk and impact of plastic pollution on marine environments and human health remains uncertain, introducing sources of further plastic pollution (such as the aforementioned lost and sunken Argo floats) is a cause for concern.

Possible pull-quote: “While UUVs may add to plastic pollution, there are also design concepts for autonomous robots able to clean up plastic waste floating in coastal regions to prevent it from reaching the open sea.” (Plastic Soup Foundation, n.d.).

4.3.4 Parallels with space missions

Space missions have a responsibility to not only keep new environments pristine, but also to not leave behind excessive debris. The field of space ethics has been active since the 1980s (Szocik et al., 2020) and concerns our exploration of a largely inaccessible, scientifically and politically interesting, remote environment — so the parallels between space and the ocean are clear.

When sending spacecraft and equipment to other bodies in the Solar System, missions must adhere to stringent guidelines on planetary protection to avoid ‘forward contamination’ – that is, to not introduce contaminating material to pristine environments. Missions must ensure that the probability of them introducing a single Earth organism into a novel habitat does not exceed 10^{-4}(0.0001) (Sherwood, Ponce and Waltemathe, 2019) in order to protect microorganisms that may be vulnerable to outside influence, and preserve any record of past or extant life.

Such microbes, including 'extremophiles', are also found in marine environments, such as around deep-sea hydrothermal vents and floors, hot springs, and salty lakes (Dalmaso, Ferreira and Vermelho, 2015). Extremophiles are especially interesting for industrial and medical uses, as they are able to thrive at the very extremes of temperature, acidity, pressure, radiation, metal content, salinity, and more (Dalmaso, Ferreira and Vermelho, 2015). As less than 10% of the prokaryotic life on Earth has been characterised, introducing contaminants into extremophile environments could damage, modify, or wipe out a potentially useful microbe or ecosystem, before we have had the opportunity to fully characterise it and explore its possible uses (in e.g. healthcare, industry, green development or environmental engineering). This utilitarian ethical perspective (see section 5) could be compared with an ethical approach based on either moral rules (e.g. the precautionary principle), or on virtues. In the latter case, introducing contaminants that damage extremophiles would not be benevolent, and would therefore be inethical.

4.4 The ethics of environmental disruption from marine robots

While UUVs bring an environmental burden, they also offer a currently unique means to improve our coverage, monitoring and knowledge of marine environments, species, and changes in climate and biodiversity (van Wynsberghe and Donhauser, 2018).

UUVs can monitor and visit sites that are too dangerous or remote for humans to access, such as the 2010 volcanic eruption of Eyjafjallajökull, the 2011 earthquake and tsunami off the coast of Japan, and sites that have been contaminated by toxic waste or oil spills. They can also approach sensitive species and explore inaccessible areas to track and monitor communities with relatively less stress than a human visitor may cause, and augment cutting-edge research at different aquatic depths and in complex underwater situations (such as at deep-sea hydrothermal vents, underneath expansive Arctic ice sheets, or to track aquatic predators such as sharks) (Yoerger, Kelley and Delaney, 2000; van Wynsberghe and Donhauser, 2018; Wadhams et al. 2006; Clark et al. 2013).

However, with this comes the ethical issue of a robot potentially creating physiological stresses for some species as a result of its presence within an ecosystem — and what happens, and who is responsible, if a robot malfunctions to cause unanticipated harm?

4.4.1 Responsibility, accountability and control

When considering the use of UUVs, safety and error are key considerations – in anything created by humans, vulnerabilities and chances for error exist, including chances for hacking (Lin, Abney, and Bekey, 2011) and 'spoofing' (when a UUV could be used to give another vehicle a false GPS position by broadcasting a fake and competing signal; Nichols et al. 2021).

UUVs also lack situational responsiveness or awareness, meaning that they could inadvertently cause harm or disruption. One can imagine a situation in which a UUV becomes stuck in a fishing net, collides with a fishing craft, sinks to damage a coral reef, disrupts elements of a delicate underwater ecosystem, or is mistaken for food by a large marine species such as a shark. As many such unique scenarios would be unanticipated, it becomes difficult to perform prior risk and probability analyses before a UUV is launched. Additionally, some unmanned vehicles cannot be perceived as having actively 'made a decision' — if an Argo float enters a shipping lane, this is not because it has decided to do so, but because its circumstances have transported it there. In such a situation, who is responsible for an outcome (such as collision with a commercial vessel)?

Many UUVs are autonomous. However, while they are commanded in the moment by their algorithm, this has been pre-programmed by a human operator. As the concepts of autonomy and accountability quickly become highly complex — can an algorithm be

programmed to always 'do the right thing'? — UUV designers and users must ensure that their software and systems remain highly transparent and are created with ethics and responsibility in mind. If a UUV causes harm, the chain of action that caused this harm to occur must be identifiable, so it can be used to prevent future harm by the UUV (and others). There is also the issue of malfunction. If a UUV starts to operate incorrectly, resources must be used to recover and either retire or fix the vehicle, adding to a) its unpredictability; b) its potential to cause environmental harm, and c) its lifetime environmental burden.
While such considerations are not unique to environmental UUVs, they must be considered in ethical robotic design and implementation. If research reveals that certain measures — for example, camouflage — decrease a robot's potential negative impact on an environment, there may be an associated ethical responsibility on designers, manufacturers and users to integrate this into a robot's design (van Wynsberghe and Donhauser, 2018).

Once a UUV has become established within an environment, a given ecosystem may adapt and begin relying upon that robot to fufill a particular role or perform a task. For example, floating man-made debris can start to accrete biofilms and algae; subsequently, larger biological organisms and a food web can develop around the man-made object. Where this involves plastic objects in marine ecosystems, these ecosystems have been termed the 'Plastisphere' (Zettler et al. 2013). Ethical issues arise when this object, unmanned vehicle or robot must be removed, for example for maintenance or at end-of-life (or end-of-research-project), and the ecosystem becomes weakened and suffers negatively as a result.

Since unmanned marine vehicles often accrete biofilms (and sometimes other biological life) and then are able to travel far between marine environments, there is also the potential for certain organisms to be translocated by the vehicle into new and unfamiliar environments. This has ethical implications when it comes to invasive alien species, as the inadvertent transport of an organism that outcompetes local species could have devastating impacts on ecosystems.

Many UUVs are created and specialised for a particular task. One example of this is 'COTSbot', a robot that autonomously visually identifies, approaches, and kills an invasive species by toxin injection — the predatory crown-of-thorn starfish (COTS) — in Queensland, Australia. Similarly, a UUV has been designed by the Lionfish Project to target lionfish, which have no direct predator (The Invasive Species Initiative, n.d.). A single lionfish can reduce a reef's fish biomass by 80% in just five weeks (The Lionfish Project, n.d.). However, with projects such as these, the ethical concerns are complex yet pressing: what are the ethical implications of programming a robot to kill, and, simply because a species is not indigenous to a habitat, is it ethical to kill them to control the environmental narrative (Inglis, 2020)? One of these ethical quandaries relates to biodiversity and conservation while the other lies in the robotics realm, highlighting the importance of interdisciplinary, and international, communication and collaboration in defining workable, effective guidance for UUV ethics.

4.4.2 Noise contamination

Unmanned marine vehicles can be driven by propellers, changes in buoyancy, waves and wind, powered by motorised equipment, or drift on ocean currents (like Argo floats) (Verfuss et al. 2019). Different types bring different levels of noise.

Some robots use passive acoustic monitoring to observe underwater species, for example, and so are limited to soniferous animals; despite their limited use, these sensors have a lower potential environmental disruption than active acoustic monitoring, which broadcasts sound waves into an environment and detects the reflected signal. Many marine mammals are especially dependent upon their sense of hearing for communication, navigation, foraging, hunting, avoiding predators, and mating (Ketten, 2002; NOAA, 2016), and sound has shown to negatively impact some species – ranging from hearing loss to behavioural change such as masking, aversion or attraction to the source of noise itself (*ibid;* Hastie, 2013). The effects of sound in the marine environment, and at environmentally relevant levels, remain unclear for many regions and species, but concern around noise – especially shipping noise – has been prevalent for decades, and is increasing with marine traffic (Erbe et al. 2019).

Some navigation systems that cannot use GPS (e.g. under thick sea ice, deeply submerged, or missions that involve long distances) use beacon-based navigational and communications systems that rely upon acoustic signals – RAFOS floats, for instance, which are used to monitor and map deep ocean currents and emit very low-frequency sound. These sounds could disrupt sea mammal communication and interfere with the navigation and communication signals used by marine mammals such as dolphins or whales (cetaceans).

Soniferous craft are split by those that use mid-frequency active sonar (sending sound into the environment and recording the returned signal) and passive sonar (receiving existing reflected sound). Research suggests that mid-frequency active sonar may harm marine mammals, especially beaked whales, by damaging their ears to cause haemorrhaging and/or disorientation (Alexander, 2009). If disorientated, mammals may surface too quickly, giving them 'the bends' (excessive nitrogen released from solution in the blood).

The potential harm caused by mid-frequency active sonar has been a point of discussion and contention for military UUVs in particular, with the US Navy invoking a number of federal exemptions to existing environmental laws (including the Marine Mammal Protection Act, Endangered Species Act, National Environmental Policy Act, and Coastal Zone Management Act) (Hoy, 2004). From 2007-2009, a case made its way to the US Supreme Court in which Naval activity was granted permission to perform operational exercises off the coast of California using mid-frequency active sonar. The Navy was initially halted after environmental groups filed a complaint, with evidence suggesting that the sonar disrupted marine mammals' normal activities; that the Navy's proposed mitigation measures were inadequate; and that the Navy's proposed activity ran the risk of harassing, harming, pursuing, wounding or killing over 170,000 marine mammals (including 466 permanent injuries to whale species). The Navy was ultimately allowed to continue with their proposed activity, as the Court ruled that "the [environmental] groups' alleged interests 'are plainly outweighed by the Navy's need to conduct realistic training exercises to ensure that it is able to neutralise the threat posed by enemy submarines'".

Many conflicts exist concerning military use of differing frequencies of sonar. Ethical issues arise here around the balancing of competing interests — e.g. military versus environmental — and how this will develop as UUVs are increasingly used, and increasing amounts of species become endangered and therefore are covered under the Endangered Species Act (given that between 10,000 and 100,000 species are estimated to go extinct every year; UNEP/CBD, 2007; WWF, 2020).

4.4.3 Interaction with marine life

There have been prior instances of marine species interacting with UUVs. In 2017, an ocean glider nicknamed 'Jack' was attacked by a shark in the Sargasso Sea (Atlantic Ocean). When the glider began to drift from its programmed course, it was collected by its operator (the Bermuda Institute of Ocean Sciences), and evidence of the attack was observed. While the shark was not seen due to Jack's lack of a visual camera, and so its species remains unclear, it caused notable damage to the glider, removing most of its rudder and pulling its tail boom upwards so the UUV lost its ability to steer (Bermuda Institute of Ocean Sciences, 2017).

Additionally, in 2013, the REMUS SharkCam glider, operated by Woods Hole Oceanographic Institution and operating off the shore of Mexico, was returned covered in dozens of bumps and bites from great white sharks (Woods Hole Oceanographic Institution,

2021). Scientists noted that some sharks “displayed signs of territorial behaviour toward REMUS SharkCam”, deliberately lurking near the UUV before suddenly striking upwards to bite the glider on its tail or mid-section in what were “most likely predatory attacks…the same way sharks hunt seals near Guadalupe Island”.
While the researchers note the scientific value in recording this behaviour as documentation of how sharks hunt in the wild (Woods Hole Oceanographic Institution, 2021), the UUV’s presence also has potential to disturb, disrupt, distress or injure individuals of the species — something that would affect the wider shark community and local ecosystem, especially given the importance of apex predators in providing ecological stability (UCSB, 2014). One way to reduce this potential impact would be to design UUVs that look and behave completely unlike prey species (e.g. seals). UUV designers and users may have an ethical responsibility to consider this potential harm when creating and launching future UUVs.

4.5 The ethics of fair benefit sharing for marine research using marine robots

Fair benefit sharing is an important goal for marine research, particularly as many areas of the ocean are not under the remit of any one nation. These ‘Areas Beyond National Jurisdiction’ (ABNJ) make up 64% of the surface of the oceans and almost 95% of its volume (Global Environment Facility, 2016).

This discussion has previously focused on the fair sharing of benefits from the use of marine genetic resources (MGR). A range of industries including pharmaceutical, agriculture, aquaculture, food and cosmetics companies can benefit from molecules discovered in the marine realm (Broggiato et al., 2014) and sharing these benefits equitably is an important ethical concern.

> *Marine genetic resources (MGR) refer to genetic material of marine plant, marine animal, microbial or other origin containing functional units of heredity, which have an actual or potential value.*

Convention on Biological Diversity, Article 2

This discussion has been given a new dimension by the development of UUVs, which promise to generate greater understanding of our oceans, in terms of its biodiversity, response to climate change, biogeochemistry and more. UUV research may also contribute economically important information, such as providing early warning of fisheries decline or the identification of commercially attractive minerals or antibiotics. It is important to consider how these new benefits might be shared between stakeholders, regions, and nations.

Box: Benefits of UUV research

- Depth of access

Due to depth limitations, the vast majority of marine research (90%) before 2005 took place at a depth of 200 metres or less (Christofferson and Mathur, 2005). UUVs can overcome these limitations (i.e. don’t need a tether) and charter new territories. (However, this also means they can conduct research across borders.)

- Climate forecasting

UUVs can collect a range of data on the state of the oceans (e.g. Argo floats/gliders mentioned in previous section). This includes data on: temperature, salinity pressure, species distribution, sedimentation, currents, CO2 and O2 levels, chlorophyll and a range of other variables. These data can be combined to understand how the oceans are responding to climate change and to predict what the climate and oceans may look like in the future

For example, unmanned gliders have been used to monitor key parameters in the Arctic, revealing how the ocean changes under different conditions, indicating that climate change may cause a lack of food availability for zooplankton in the region (Paterson, 2018).

As part of the EUREC4A (Elucidating the Role of Clouds-Circulation Coupling in Climate) project, scientists have used a range of unmanned marine vehicles, including wave gliders, seagliders, saildrones and Argo floats to study how the upper ocean and lower atmosphere control the development of marine clouds in Barbados. This will help scientists to understand how fast the planet is warming and improve weather models (NOAA, 2020).

- Weather/hazard data

In addition to long-term climate forecasting, UUVs can help to improve predictions of shorter-term weather events, such as storms. Unmanned gliders equipped with salinity and temperature sensors have been used by the NOAA (NOAA, 2019) to improve hurricane predictions for example.

- Biodiversity monitoring

The large amount of data that can be collected by UUVs, including images of the seafloor, can be used to investigate species diversity and distribution. This can ultimately help scientists to understand the drivers of species change (University of Plymouth, n.d.).

- Fisheries data

Unmanned vehicles equipped with acoustic ‘fishfinders’ (echosounders) can be used to study migration patterns in fish and predator-prey relationships. A study of saildrones equipped with these echosounders detected a similar number of fish compared to a traditional research ship (De Robertis et al., 2019). Although saildrones cannot identify the species of fish, they offer a wider spatial and temporal range of observations than traditional methods.

- Decommissioning oil and gas installations

Decommissioning is an important task with significant environmental impacts. UUVs can automate environmental monitoring, improving the resolution of the data, protecting the environment, and reducing cost compared to conventional approaches (Jones et al., 2019)

- Seabed maps

UUVs can help to construct detailed maps of the seabed, which can be used to understand how the ocean and climate has changed throughout history. UUVs are equipped with sonar to penetrate the seabed and reveal previous sedimentation patterns, as well as other equipment to measure ocean currents, temperature, carbon dioxide, chlorophyll, nitrate and oxygen levels (University of Gothenburg, 2017).
One good example of fair benefit sharing is the Seabed 2030 Project, which aims to create a complete map of the ocean floor, with partners using AI to both collect and process the data (Patton, 2021; The Nippon Foundation-GEBCO Seabed 2030 Project, 2021).

- Deep sea mining

UUVs can also be used to mine rare earth metals found in the seabed (Stoichevski, 2019; Weedon, 2019). For example, the EU ROBUST project uses autonomous underwater vehicles to identify manganese nodules (Sartore et al., 2019).

//END BOX

4.5.1 Navigating national and regional borders

Issues and principles of marine boundary delimitations are not new. Sovereign control over territories is expressed in concentric limits surrounding the coast (or certain features), and include the territorial sea (12 nautical miles/nm from the coast), the coastal shelf (24 nm from the coast) and – since the instigation of UNCLOS in 1982 – the Exclusive Economic Zone (200 nm from the coast, except where the space between two states is less than 400 nm). With the introduction of the EEZ, more states' interests in – and claims to – marine natural resources has come to the forefront.

Differing interpretations of the law of the sea can lead to disputes over jurisdictional rights and interests, and a large number of boundary disputes still exist between states today (Østhagen, 2020). These maritime boundary disputes and differing interpretations are a well-understood ethical problem – however, they may be acquiring rising importance as human interactions with the marine space are becoming ever more intense and complex. Changes deriving from increasing resource pressures, international commodity prices and new technologies, as well as changes to the oceans (and ocean biochemistry) as a result of climate change are putting some marine disputes back on the agenda. For example, within, across and between EEZs, environmental factors (such as climate change) are causing changes in the distributions of fish stocks, which has an impact on the productivity of national fisheries. New technologies also allow access to new sources of minerals on the sea bed, for example polymetallic nodules or cobalt-rich crusts, which have been identified as having potential economic interest.

States cannot deny passage through their EEZs, but they can deny access to marine resources and apply environmental regulations within their maritime zone. This means that technologies that enable greater control, observation and monitoring of the marine environment (e.g. UUVs, subsea installations, satellites) can send data back to home states from foreign states' EEZs. Research institutes, regions and countries also have different marine research capabilities. Some more developed countries are able to conduct research in the waters of less developed countries that do not have the technological capacity to do so. If a UUV developed by one nation is deployed in the waters of another, what are the ethics around the discoveries it makes? For example, a UUV could identify commercially viable materials in the waters of the other state, or identify biochemical changes that signal a decline in fisheries. Is the owner of the UUV morally bound to inform the nation of their findings, and enable them to share in the potential benefits of their discoveries? There are also ethical questions about the sharing of informational resources, such as seabed mapping (which has potentially sensitive military uses).

An extension of this ethical problem comes when we consider the potential geopolitical impacts of unmanned vehicles becoming lost or disabled in some way. For example, if an UUV becomes damaged and loses contact with its sending research centre somewhere in another state's EEZ, then washes up on that state's coastline: how does the state know that the UUV is in fact disabled? How does the state know that the UUV hasn't been sending sensitive data about the state's territorial sea back to the home state?

With regard to marine pollution caused by unmanned marine vehicles, and problems of plastic waste discussed earlier in the brief, the loss of UUVs and other unmanned vehicles also has implications for marine littering and pollution in other states' waters and may be out of line with certain national environmental regulations. At present, there is very little way to control this impact, so this could spur a greater concentration on the development of retrievable vehicles.

The addition of greater numbers of marine robots will not add a new hazard, but there may be some new or greater impacts that make it more pertinent to address the ethical questions of how to share both the benefits and the risks of marine research fairly.

4.5.2 How to share the benefits of research?

The technology that underlies UUVs is expensive to build and difficult to access. This means only the wealthiest nations and research centres have access to UUVs for their research. This dynamic could be made more equitable by committing to **data sharing** and **open science protocols**. Openly sharing the data obtained from unmanned missions (e.g. Argo floats) is one way to share the benefits of research with those in other nations. It allows those in less developed nations, who may not have the resources to launch their own UUV missions, to conduct their own research using the open access data.

Fair benefit sharing also is one of the key ethical concerns surrounding the use of all forms of AI. It is considered an important goal to ensure that the benefits of AI do not accumulate in the hands of the few (EPRS, 2020).

The Convention on Biological Diversity has laid the foundations for access and benefit sharing of genetic resources (all living organisms), including those found in marine environments. This international legal instrument includes provisions which are designed to ensure that physical access to genetic resources is facilitated and benefits from their use are shared equitably, at the same time as exploitation is balanced with environmental health. Practically, however, the cases and precedents for implementing the CBD are still very much in development.

With regard to mineral resources, the International Seabed Authority is in the process of finalising a Mining Code that will regulate and enable the exploitation of minerals from the sea floor. UNCLOS states that activities must be for the “benefit of mankind as a whole” (UNCLOS, Art 140, p1). A core component of Part XI of UNCLOS is the ‘Common Heritage of Mankind’ principle, which includes the concept of fair benefit-sharing and an obligation to balance exploitation with the environment. This was an issue explored in 2018 in a workshop of 50 experts from diverse backgrounds (German Environment Agency, 2019), which made recommendations for how to share benefits from mining resources fairly, including how payments should be made.

4.5.3 Sharing the benefits in the marine research labour market

As well as benefits, increasing use of automation and unmanned vehicles may lead to job losses. The increasing use of UUVs and other unmanned marine craft is set to have some impacts on job availability and labour relations in the marine research sector. As automation increases, fewer people will be required on board ships – and, indeed, the ‘people-space’ may be swapped out for space required for new fuel sources or data centres.

The types of tasks that AI could replace on a ship are manual tasks and administrative tasks, as well as analytical and calibration tasks. Skillsets are shifting towards more specialised programming and technological skills, and towards land-based operation centres (Lloyd’s Register, 2017), meaning that there is expected to be less opportunity for seafaring jobs in future.

The loss of these jobs aboard ships could also be balanced by new jobs and opportunities being created on land. This could provide opportunities to work in the marine sector that were previously not open to all – for example, for people who are disabled or unable to go to sea for several months at a time, meaning the benefits of the marine research sector could be shared more fairly as a result of increasing automation.

4.6 The ethics of energy in marine robots

The human and environmental costs of shipping are vast. Low-grade marine fuel oil contains 3,500 times more sulphur than road diesel (Wan et al., (2016). Particulates emitted from ships also cause 60,000 cardiopulmonary and lung-cancer deaths each year worldwide (Corbett et al., (2007).

Ships emit nitrogen oxides (NOx), sulphur oxides (SOx), carbon dioxide and particulate matter (PM) into the atmosphere. Worldwide, from 2007 to 2012, shipping accounted for 15% of annual NOx emissions from anthropogenic sources, 13% of SOx and 3% of CO2 (Smith et al., (2014).

Unmanned underwater vehicles offer a desirable alternative. Most are powered by rechargeable lithium batteries or primary batteries which do not produce carbon emissions as a waste by-product. Even if you count the embodied carbon used in their production, transport and disposal, they are much more environmentally friendly than a conventional research ship.

New observation technologies and techniques will advance our understanding of the ocean's impact on climate, weather, and food security, as well as societal issues such as management of the energy, ecosystems, and raw materials of the ocean.

There have recently been huge advances in AI powered smart sensors that could help us answer these questions and more. However, these sensors require more power than typical batteries can provide.

In other words, subsurface ocean observation and exploration remain fundamentally constrained by an energy bottleneck. Therefore, if AUVs are going to take on these additional job roles, we will need to either develop more efficient and high-power batteries, or use some other fuel source instead. Private companies, research bodies and governments around the world are throwing their weight behind fuel cells and renewables. However, each of these power sources have ethical implications, including their impact on the environment and on human safety.

4.6.1 Current energy sources

4.6.1.1 Batteries

Without the supply of oxygen from the atmosphere, internal combustion engines are not practical and so almost all the AUVs on the market are powered by batteries. Of these, the majority rely on primary lithium batteries due to the more expensive upfront cost of rechargeable batteries.

Benefits

As a consequence, AUVs contribute significantly less towards global greenhouse gas emissions than ships running on marine diesel. Batteries also fit well into AUV hulls, can supply power on demand, work during submerged operations, and are reliable and silent.

Challenges

However, the technology is not without its drawbacks: for example, safety. Because large lithium-ion batteries can become hot enough to ignite nearby materials or even erupt into flame when damaged, they can present a safety concern when transported on board marine vessels.

The main issue with batteries, however, is that they can only store a finite amount of energy. The amount of energy available from 1kg of the best batteries is about ten times less than that available from the same quantity of diesel fuel. The total energy capacity of a small AUV may only be a few kilowatt-hours (kWh); while larger 21-inch-diameter AUVs may have battery packs with capacities in the order of 10 kWh or more (Dhanak and Xiros (2016).

This means that the operating time for most AUVs is limited to just tens of hours. To conserve energy, AUVs must therefore travel slowly – at just 1.7ms−1 compared to 5 to 10ms−1 for a ship (NOC website). This substantially limits the range of AUVs.

It also means that AUVs require periodical recharging from a dedicated host platform or support vessel. In most cases this will be a ship, which runs on marine diesel and therefore contributes to carbon emissions. In addition, batteries are usually heavy and take up around 20% of the volume of small AUVs (Griffiths et al., (2004).

Nevertheless, some AUVs can run for longer periods. The lithium battery powered Konsberg HUGIN® Endurance offers missions of up to 15 days duration, and has a range of 2200 km - equivalent to the sailing distance from New York City to Cuba (Konsberg website).

Some lightweight AUVs such as gliders can also operate for months at a time before a recharge is needed. For instance, the NERC Oceanids project includes an Autosub Long Range AUVs which is capable of being deploying for up to three months (NOC website).

With a small sensor load, a glider is able to last six to nine months at sea. However, glider missions frequently last up to 3 months and cover distances up to 1,800 kilometers. New commercial gliders are also available that can travel 10,000 kilometers (up to 6,000 m depth).

Future developments

According to a report by Lloyd’s Register Group Ltd, QinetiQ and the University of Southampton on Global Marine technology trends (Lloyd’s Register Group Ltd, QinetiQ and University of Southampton, 2017), battery technology is developing rapidly. Recent breakthroughs include lithium-sulphur, lithium-air and aluminium-ion batteries. Whilst these are still in their early stages of development they are not yet commercially available. These types of batteries may prove to be revolutionary for the maritime sector.

According to the report, another emerging technology that may compete, or compliment, battery technology, is the supercapacitor (like an ordinary capacitor, but it stores considerably more electrical charge). Unlike batteries they charge almost instantly, but do not store as much power. In the future it is likely that supercapacitors will be used more often, particularly when there is a need to store and release large amounts of electricity very quickly.

Other advances in battery technology include the lithium seawater battery developed by the PolyPlus Battery Company. The battery has an energy density of up to 4 MJ/kg, twice that of primary lithium-ion batteries and almost an order of magnitude higher than rechargeable lithium-ion batteries (Davis and Sherman, 2017).

Ethical considerations

AUVs represent an environmentally friendly alternative to ships, which are powered by marine diesel and other fossil fuels and contribute significantly to global carbon emissions.

However, while batteries do not directly release pollutants and global greenhouse gases, the ethics of how they are produced, transported and disposed of must also be considered.

A 2016 investigation by Amnesty International found children and adults in southern DRC working in hand-dug cobalt mines facing serious health risks (Amnesty International, 2016). Cobalt is a key mineral found in batteries, and Amnesty's research has linked these mines to the supply chains of many of the world's leading electronics brands and electric vehicle companies.

While demand for cobalt may reach 200,0000 tons per year by 2020, no country currently legally requires companies to publicly report on their cobalt supply chains. As more than half of the world's cobalt is found in southern DRC, the chance that batteries powering AUVs are manufactured using supply chains with child labour and other abuses is high (Amnesty International website).

Amnesty International has also documented violations of the human rights of Indigenous peoples living near lithium mines in Argentina.

The environmental impact of producing batteries is also a concern. Most of the current manufacturing of lithium-ion batteries occurs in China, South Korea and Japan, where electricity generation remains dependent on coal and other polluting sources of power.

Meanwhile, rising demand for minerals like cobalt, manganese and lithium has led to a surge in interest in commercial deep-sea mining, which studies predict will have serious and irreversible impacts on biodiversity (van Dover et al., 2017).

There is also chance that batteries, which contain various hazardous materials, could be irresponsibly disposed of, contaminating soil, water and air. When it comes to battery disposal, some AUVs such as Floats and Drifters are seen as disposable, however this leads to lithium batteries being dumped in the ocean, where they could harm marine life.

Another concern is the supply of batteries in the future. Every major car retailer is preparing to switch from fossil fuels to electric and hybrid cars. There is a worry that the world's battery supply chain, from mines to manufacturers, will fail to keep pace, leading to a bottleneck that will slow the fight against climate change (NPR website).

4.6.1.2 Fuel cell systems

Long-endurance AUVs that can travel further and for longer without the need for refuelling would allow for more challenging mission types, such as under ice seabed surveys, long-distance ocean current monitoring at constant depth, fish shoal tracking and ultra-long pipeline inspection.

The need for a carbon-intensive mother ship could be eliminated altogether if the range of the AUV was sufficiently high that it could be launched from a pier.

Fuel cell systems offer the possibility of extending the endurance of AUVs significantly (Davis and Moore, 2006; Sawa et al., 2005; Hasvold et al., 2006).

In a fuel cell, the chemical energy stored in two or more reactants is converted to electrical energy by an electrochemical process (Hacker and Mitsushima, 2018). The reactants are continuously supplied from an external storage media.

Reactants commonly used include hydrogen, oxygen, aluminium and ammonia. These can either be produced separately, or within the vessel itself. For instance, in 2018, General Atomics completed a 46-day demonstration of an AUV powered by hydrogen generated by the reaction between aluminium and water (General Atomics, 2018).

MIT spinout company L3Harris has also developed an aluminium-water fuel cell that it claims can increase the endurance of AUVs by up to ten times.

The power system consists of three main components: an activated aluminium anode; an aqueous alkaline electrolyte; and a hydrogen-evolving cathode. When a UUV equipped with the power system is placed in the ocean, sea water is pulled into the battery, and is split into hydroxide anions and hydrogen gas. The hydroxide anions interact with the aluminium anode, creating aluminium hydroxide and generating electricity. Both the aluminium hydroxide and hydrogen gas are jettisoned as harmless waste.

The company claim that the technology is ideal for unmanned 'dirty, dull, and dangerous missions, such as mine-sweeping or pipeline survey, thus protecting human lives and minimising on-station, maintenance, and labour costs associated with operating ships, aircraft, or other expensive assets (L3Harris website).'

Benefits

Although fuel cell systems create waste products that are released into the ocean, these products are usually not as harmful, compared to the exhaust of fossil-fuel powered engines. The fuels also carry less risk of explosion, and in many cases can be transported safely even via commercial airlines. Aluminium fuel for example is reliable, easy and safe to handle, and reacts quietly.

Challenges

However, several challenges exist for underwater operation of fuel cell systems, explaining why they have yet to become a commercial success. For instance, fuel cells are much more complex compared to batteries (Weydahl et al., (2020). As a result, they require extensive maintenance routines and are more likely to fail. Refuelling fuel cell systems also involves handling highly reactive, and often expensive, chemicals, making human safety an issue. In comparison, batteries are easy to operate and simple to recharge. Additionally, fuel cells for AUVs are a new technology and come with a substantial development cost.

Other difficulties include storing the reactants. While fuel cell systems have a much higher energy density than batteries, they tend to be bigger and heavier. Compact storage of hydrogen and oxygen is difficult, which is a problem for small AUVs as it affects their manoeuvrability.

Heavy fuel cell systems can also affect the buoyancy of AUVs, making them unstable and less manoeuvrable in the water at low speed. To protect them from corrosive seawater, sensitive equipment, such as the fuel cell stack and electronics, must be placed in a pressure tight, sealed container. This represents its own challenges, as water from the fuel cell must be collected otherwise humidity in the tank leads to condensation. Condensation can cause electronics or other sensitive equipment to malfunction or corrode inside the tank.

Another challenge is accumulation of hydrogen or oxygen in the container. This introduces the risk of gas leakage and combustion within the sealed hull of an AUV.

Ethical considerations

Fuel cells would considerably extend the capabilities of AUVs, and hence would reduce carbon emissions from shipping. They could also allow AUVs to do more dangerous jobs, and minimise the maintenance associated with operating ships, protecting human lives.

In addition, fuel cells emit no carbon dioxide. They also do not emit poisonous pollutants such as NO_x and SO_2.

However as with batteries, there are ethical considerations regarding how reactants such as hydrogen, ammonia and oxygen are produced, transported and disposed of.

The environmental impacts of fuel cell use often depend on how the reactants are produced. For example, ammonia is commonly made using methane, water and air, and consumes a lot of energy (producing around 1.8% of global carbon dioxide emissions; Royal Society, 2020). However, there have been recent advances in 'green ammonia', using water electrolysis and nitrogen separated from the air, with processes powered by sustainable electricity.

Hydrogen can also be made using renewable power. For instance, solar panels can convert sunlight into electricity, which is then used to split water (electrolysis) into hydrogen and oxygen. In this scenario, fuel cell powered AUVs would have no significant emissions of greenhouse gases.

However currently roughly 48% of the worldwide hydrogen production is accomplished by steam reforming of natural gas, 30% by processing crude oil products, 18% by processing coal and 3% as a byproduct of the chlor-alkali process (Upadhyaya et al., 2004). All of these processes release carbon.
Another issue with production and transport of hydrogen is safety. Hydrogen ignites in air at very low concentrations, and ignition can be instigated by something as simple and commonplace as a static electric spark.

4.6.1.3 Renewable power

The oceans are an ideal source of renewable power. Harnessing wind and wave energy in particular could extend AUV mission durations and capabilities, and allow AUV systems to be remotely and renewably recharged at sea. This would also remove the need to carry heavy and cumbersome energy reserves for entire missions and remove the need for expensive and climate polluting support vessels (Townsend, 2016).

Systems that can convert waves and currents to electrical power could play a significant role in meeting the energy needs of the next generation in autonomous technologies (Ayers and Richter, 2016).

For instance, Californian company Liquid Robotics has developed the Wave Glider, an autonomous, underwater vehicle propelled by wave and solar energy which can operate for up to one year with no fuel.

The AUV consists of a surfboard-like float tethered to an underwater float about 8 meters below the surface. The underwater float has six sets of 'wings' which it uses to harness waves. While the device is wave propelled, it relies on solar panels on the surface float to generate power for instruments and sensors.

Other solar powered AUVs include SAUV-II (Crimmins et al., 2006), Autonaut (Autonaut website) and C-Enduro (Asv Global website). A prototype thermal energy harvesting underwater vehicle, the SOLO-TREC, has also been developed, which uses a phase-change material (a waxy fluid) that melts and expands in warm water at the surface and solidifies in cooler deeper water to drive a hydraulic generator and provide power (Yi, 2013).

Gliders have also been developed using ocean temperature gradients and battery power to provide propulsion (Davis, Eriksen and Jones, 2002). Researchers from Southampton University also developed an AUV capable of harnessing energy from waves in situ (Townsend, 2016).

Wind powered AUVs have also been developed, for instance the C-enduro uses a deck mounted wind turbine to generate power and the Submaran uses a fixed wing sail for propulsion (Ocean aero website).

Challenges

The obvious limitations of wind, solar and wave energy powered autonomous vehicles, is that they restrict vehicles to surface, or near surface operations, and, for some types, to particular wind routes. For this reason, they represent only a very small proportion of AU vehicles.

Future developments

According to a recent review (Whitt et al., 2020), the most probable near-term, in situ candidate energy sources include the following:

- Solar photovoltaic panels
- Wind turbines, either horizontal axis or vertical axis

- Wave energy converters, which convert the kinetic and/or potential energy in surface waves to electricity
- Current turbines in tidal or ocean currents, which operate on a similar principle to wind turbines; and
- Thermal gradient energy conversion

Ethical considerations

Harvesting wind, wave and solar power offers a truly green way of powering the next generation of AUVs. However, as this type of energy is really only present at the ocean surface, AUVs relying on renewables would either need to stay close to the surface, or have an efficient way of storing the electricity generated.

4.6.1.4 Nuclear power

Nuclear power is particularly suitable for vessels which need to be at sea for long periods without refuelling, or for powerful submarine propulsion. Currently, over 160 ships are powered by small nuclear reactors. Most are submarines, but they range from icebreakers to aircraft carriers.

Ethical considerations

In the future, constraints on fossil fuel use in transport may bring marine nuclear propulsion into more widespread use. However, so far, fears about safety and expense have meant that they have not been considered for use in AUVs.

One exception is Poseidon, a nuclear armed and nuclear powered UUV currently being developed by Russia. Russia has stated the weapon will be ready for service by 2027, has and completion of the project will require the development of a reliable, miniaturised nuclear reactor for the UUV.

4.6.2. Supporting ships

Currently AUVs are usually launched, recharged, services and retrieved from research ships. Not only do ships produce carbon emissions and toxic pollutants such as NO_X and SO_2, they can also release toxic and polluting chemicals when scrapped, exposing workers to hazardous fumes (Wan et al., 2016). These include asbestos, heavy metals and oils. The EU has laws requiring that ships registered in Europe be broken up only in licensed yards that meet strict guidelines. However, many ships are scrapped in India, Bangladesh, and Pakistan where there are no regulations (Hossain, 2015). In Bangladesh for example, 40,000 mangroves — trees that stabilise many tropical coasts and are habitats and breeding grounds for many species — were chopped down in 2009 alone to accommodate shipbreaking yards. The pollution from scrapping there has caused an estimated 21 fish and crustacean species to become extinct. And reportedly, each week one worker dies and seven are injured in the scrap yards of Bangladesh.

Investment in on-shore infrastructure is also needed in order to refuel ships in renewable ways – this will need to be built and developed and without this, the marine research sector will not be able to go carbon neutral.

4.6.3. Charging platforms

One way to extend the capability of AUVs so that a research ship is not necessary at all, is for unmanned underwater vehicles to dock at a recharging platform so that their batteries can be recharged at sea.

According to a report by the U.S Department of Energy on Powering the Blue Economy (U.S Department of Energy, Office of Energy Efficiency & Renewable Energy, 2019), the main barriers preventing adoption of this technology is the need for significant investments in infrastructure (moorings with satellite communications and large quantities of batteries), AUV reliability and inherent docking risk, and the comparatively high cost of scientifically equipped AUVs. Other risks include additional danger to vessel crews, increased carbon emissions, and the potential for petroleum spills.

However, many of these disadvantages would be overcome if AUVs could be recharged underwater without surfacing. Underwater recharging would reduce the need to recall vehicles to the surface as frequently; save time and resources; improve human safety; increase mission duration, range, and stealth; and reduce carbon emissions.

Recharge stations powered by marine energy could harvest power continuously, and—when paired with battery banks—allow reliable, on-demand recharging of vehicles.

They could include temporary or permanent installations, or move with AUVs as they conduct mapping or search operations.

According to the U.S Department of Energy report, marine energy is the most viable option for powering underwater vehicle recharge stations. Hydrogen-oxygen fuel cells are also a viable underwater power source, but require a consistent and reliable supply of hydrogen for fuel. Diesel generators would need to be surface-based and would require frequent refueling and maintenance, leading to high costs and risk of spills.

Other renewables, such as solar and wind, could be even less suitable, as AUV charging would likely take place underwater, and solar and wind applications by their nature must be mounted at the surface. Solar panels would also need frequent cleaning from salt spray and bird droppings.
Defense contractors and laboratories are likely to be early adopters of underwater marine-energy-powered recharge devices. For instance, MBARI has designed and built two experimental docking stations for their Dorado and Long Range AUVs (MBARI, 2018).Teledyne Energy Systems is also developing the Sea Floor Power Node for deep-water AUV recharging applications using fuel cell power with refillable reactants (Utz et al., 2018).

4.6.4. Conclusion and overall ethical considerations

Most AUVs are powered by rechargeable batteries, primary batteries or fuel cells. All of these technologies are reasonably green and environmentally friendly compared to research ships, even when the embodied carbon used in their production, transport and disposal is accounted for.

However, there are ethical considerations for the UK research community in the production and disposal of batteries in particular. It is vital that the human rights and safety of people working in cobalt mines, or people living close to them are protected. It is also important that deep sea mining for minerals in batteries does not harm biodiversity, and that batteries are safely disposed of.

Finally, there is a need to balance the environmental harm that can come from using AUVs and research ships with the importance of studying the oceans for combating climate change. Without studying the impact of human activities on ocean chemistry, biodiversity, weather and climate change, it will be impossible to understand the changing earth processes and may make it harder to make the societal shifts needed to reduce carbon emissions.

5. Methods for predicting and avoiding/reconciling ethical hazard

5.1 The problem

The problem of determining the ethical impacts of autonomous systems in oceanography is three-fold. Firstly, our speculations about any emerging technology tend to be poorly grounded. Secondly, by their nature marine autonomous systems will tend to touch many global stakeholder groups who may inherit different ethical frames. Finally, speculation about a technology *in general* is less useful than considering its particular applications; and these applications in many cases have not yet been conceived.

5.1.1 Ethical impacts of new technologies are hard to predict

In his chapter on the Ethics of Emerging Technologies (Hansson, 2017), Brey defines Emerging Technologies as technologies that are new, innovative, and still in development, and are expected to have a large socioeconomic impact. He makes the point that, since emerging technologies are still in the development phase, our discussions of their impact are of ethics *in posse*. Even so, or perhaps because of this, predicting ethical impacts and consequences of emerging technologies is a valid and important endeavour.

Before a technology is fully realised and exploited, becoming by this process 'entrenched', we may have a greater capacity to affect the course of its development, to forestall its negative impacts, and perhaps to save billions of pounds of investment on a technology which a shift in public opinion eventually precludes from use[1]. Although predicting the outcomes of emerging technologies may be a fraught process, it is clearly worthwhile.

[1] This argument, further vivified by the Swiss participatory democratic system which could see a publicly initiated referendum voted upon with legally-binding consequences, was one of the motivators for an extensive analysis of how (lethal) autonomous systems could be ethically assessed (Christen *et al.*, 2017), commissioned by the Swiss military to help them decide how to shape future investment

5.1.2 The marine environment is global and touches many stakeholders who have different interests and ethical frames

There are many classes of stakeholders, that is, persons, organisations or groups with an interest and influence on the marine environment and its governance and regulation. In their paper, Newton and Elliott recognise six main types of stakeholder, being those who extract resources and goods, those who input pollutants of various types, regulators, those affected by impacts, influencers such as NGOs, and beneficiaries from the environmental services of the marine environment (Newton and Elliott, 2016). The breadth of views and interests represented within this typology is striking, and it is clear that these may be brought into conflict through the introduction of an emerging technology to the marine environment. This problem is further magnified by the connected nature of this environment; material discharged in one sea may cause impacts far from its point of origin (Audrézet *et al.*, 2021). One might argue then that the stakeholder groups, with their different drivers, are likely to be still more complicated by the cultural diversity of the communities from which they originate. Marine pollution is a global problem (Villarrubia-Gómez, Cornell and Fabres, 2018), and we might expect the impact to be most severe on the poorest and most marginal communities that depend upon subsistence fishing (Jackson and Loeffler, 2018). Different cultures have different traditions and ethical framings and there is no 'Global Ethics' (Kim, no date), and nor perhaps, any prospect of such a thing arising.

5.1.3 New artefacts will require new assessment; it is impossible to assess 'the technology'.

Floridi and Strait distinguish carefully between a 'technology', such as robotics, and an 'artefact', the latter being a 'physical or digital product, service or platform created out of a technological field' (Floridi and Strait, 2020). While it is possible to speculate upon the ethical impacts of technologies through considering their generic qualities, it might be more focussed and useful to base our investigations in forecasting the ethical implications of any particular artefact (Brey, 2012). This suggests that it will be an ongoing task to examine the ethical (and other) impacts of autonomous artefacts engaged in oceanography.

5.2 Frameworks for predicting ethical impacts

Given the status of emerging technologies, attempts to predict ethical impacts will be more speculative than might be the case with an entrenched technology. However, this leads to pitfalls. Less-defined technologies, having future relations to the social, biological and physical environment in which they will be deployed, may present us with little prior experience and few examples on which to base our understanding. On the one hand, we should not be paralysed by this lack of concrete data from speculating about their impacts; on the other, we must avoid flights of science-fiction fancy. Fortunately, numerous methods to forecast the impacts of technologies have been developed, and ethical concerns have been increasingly considered within such frameworks.

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decisions. Beyond the moral case, buying killer robots is a wasted investment if public opinion declares they can't be used!

Discussions about Responsible Innovation (RI) predate by decades the EC focus on 'science with, and for, society' that have become known as Responsible Research and Innovation (RRI). RI focuses on the futures which will be created through (technological) innovation, and attempts to enable us to take collective responsibility for these futures, rather than simply leaving them to chance. The main elements which need to be considered in an RI framework are Anticipation of outcomes, consequences and risks, Reflection on the drivers and contexts for innovation, Inclusion and the invitation of open discourse at all stages of the project and with all stakeholder groups, Openness of communication and data, and Responsiveness to changing technologies, societal values, and emergence (Owen and Pansera, 2019). Within the UK, the EPSRC was one of the first to embrace RI with the AREA (Anticipate, Reflect, Engage, Act) Framework in 2013 (Owen *et al.*, 2013). Reijers et al. present an excellent overview of the publications within the field, and distinguish between '*ex ante*' methods which attempt to forecast problems before projects start, '*intra*' methods which operate during the design and development process, or '*ex post*' approaches for use when development has finished and the resultant artefacts are in operation (Reijers *et al.*, 2018). We would suggest that the proper focus for our current discussion would be around '*ex ante*' methods, in an effort to maximise good, and minimise harm; and that this is particularly important as we discuss emerging technologies and the artefacts which may result from them.

5.2.1 What characteristics should such a framework have?

There have been a number of papers which review different '*ex ante*' methods that can be applied to the applications of emerging technologies. Methods focused on Scenario Planning (Amer, Daim and Jetter, 2013; Crawford, 2019) seem inappropriate, for their scope is too broad, which seems also true of Future-Oriented Technology Assessment (FOTA) (Nazarko, 2017). In their recent review, Floridi and Strait (*ibid*) assess a number of different approaches to Ethical Foresight Analysis.

- Methods based on crowdsourced predictions, focus groups and a community of experts (such as Delphi)
- Methods which can be grouped under the heading of Technology Assessment (TA) (Guston and Sarewitz, 2020) rely on modelling, impact analyses and dialogue between stakeholders, with surveys, opinion polls and content analysis to track changing perceptions and moral beliefs.
- Debate-Oriented Frameworks such as Ethical Technology Assessment (Palm and Hansson, 2006) attempt a continuous process of debate about ethical concerns which are fed back throughout an iterative development cycle.
- Far Future Techniques such as the Techno-Ethical Scenarios Approach (Boenink, Swierstra and Stemerding, 2010) forecast over longer timeframes and involve generating 'moral controversies' using an ethics model to look at how a new technology might be viewed after its introduction and use.
- Government and Policy Planning techniques such as ETICA (Floridi, 2014) generate future usage stories for analysis by communities of experts from different policy perspectives, e.g. law, gender, etc, which are then compared with common issues in related technologies, and finally ranked to formulate policy decisions.
- Combinatory Techniques such as Anticipatory Technology Ethics (ATE) (Brey, 2012) consider the technology as a whole, artefacts that result from it, and the consequences of their application at the same time.

These methods have a number of common factors. They tend to be iterative, are informed by discourse with numerous stakeholder groups, and to some extent deal explicitly with the changing moral landscape within which decisions are made. In some circumstances they can suffer from the drawbacks that they add significant cost, may require an explicit recognition of the impacts of other technologies within the originating organisation, and can require information leak outside the organisation to stakeholder groups and to the ethical auditors themselves.

Of course, whatever method of ethical foresight analysis is chosen, so far we have not addressed the question of 'whose ethics - and why'? As mentioned above, the capacity of the interconnected seas to carry material from one area to another may cause impacts to be considered by peoples with different cultures, and hence different ethical frames. Within any one society, moral change occurs over time; consider for example the changing attitudes within the UK over the last 50 years to homosexuality, race, single mothers, etc., and the moral frame within which we understand technologies is itself formed by the interaction of society with applications of this technology. Discussion of the ethics of an artefact can only be conducted with a clear understanding of the ethical frame; to put this in engineering terms, what are our metrics for success, *what does 'Good' look like?*

5.3 Ethical frames

There are many normative ethical frames which have been the subject of philosophical and religious discussion since ancient times. Broadly speaking, they can be divided into two types; those which focus on the intrinsic value or disvalue of an action, and those which argue whether an action is *in itself* right or wrong. The former, consequentialist ethical theories such as Utilitarianism, consider actions to be preferable if they maximise some quality, such that the ends can sometimes justify the means if through a wrong action, greater good can be achieved. For example, in classic Utilitarianism, this quality is the presumably universal preference for pleasure over pain. This may seem an attractively simple proposition lending itself to a 'spreadsheet of ethical value', but as one quickly understands, comparing the relative value of actions which have effects of differing type and severity on stakeholders that themselves vary in type, identity, number, nationality and culture goes far beyond simple 'trolley problems'. The latter class of ethical frame includes 'virtue' ethics which focus on the character of a person, and deontological 'duty' ethics which focus on the rights and responsibilities of the person. If consequentialist approaches suffer from the difficulties of comparing apples with oranges, virtue and duty ethics suffer from relativism and a lack of absolute authority; one person's good is just as good as another's. It has been observed that teaching engineering ethics as a matter of professional *duty* promotes the spectator's point of view instead of the actor's, and it has been suggested that education is better served by a focus on virtue ethics which positions the engineer (or scientist) as an active moral agent (Whitbeck, 1995).

In spite of these difficulties, we still need to define our ethical motivation. What is Good in the context of Oceanography? In our conversations with the NZOC team, we have heard on several occasions hints to the emotional value of the field to its practitioners; that a love of the Sea and their attachment to it motivates their work and their passion for the field.

In his discussion of Virtues and Practices in the context of Engineering Ethics, Miller suggests;

“There is an important distinction to be drawn between practices which have no raison d'etre other than the particular excellences and enjoyments which they allow to participants (I shall refer to such practices as 'self-contained') and practices which have a wider social purpose (I shall refer to these as 'purposive').” (Miller, 1984)

Non-purposive practices cannot be finally satisfied. While a team can win a game of football, we cannot imagine a match’s outcome which means that Football as a pastime is over, decided, and no longer a matter of contest. In contrast, purposive practices can be satisfied; an external social purpose can be achieved. What then is the purpose of Oceanography, and can it be satisfied? It would seem that the study of a dynamic system that constantly changes can never be concluded. However, a large part - perhaps historically, the most part - of Oceanography is motivated by social purpose and expected to deliver results that are either directly or indirectly of service to humanity, often with some focus on the interests of the nation commissioning the work.

This suggests that our definition of ‘good’ should address human flourishing (to address social purpose), but should also address the stewardship of a flourishing marine environment as well. Beyond the immediate social purpose there lies the duty to the environment, and this duty may speak to the emotional bond of Oceanographers with their discipline. For this reason, it might be useful to consider Environmental Ethics (Taylor, 2011) as we seek to understand how to define the ethical framing for this work as this may provide the primary stakeholders (the Oceanographers) with ammunition to bolster their claim to do good.

Before leaving this section we must return again to the global reach of the Sea, and the global impacts of our actions in and on it. Global stakeholders may require the assessment of multiple ethical framings. For example, Chinese tradition and contemporary Chinese politics place an emphasis on the state above the individual, and it has been suggested that the Chinese worldview will continue to be dominated by the goals and needs of the Chinese State (Allen, Lloyd and Peer, 2019). This might challenge framings which elevate the primacy of individual autonomy, or the virtue of the individual (though of course, individual virtue has long been cherished in China in Taoist and Confucian tradition). Another ethical framing which seems pertinent is the emerging Islamic ethics of technology (Raquib, 2015). Approximately 19% of the world’s population are Chinese, and about 25% are Muslim, so both these ethical traditions should be given consideration.

5.4 What sorts of artefacts might need to be assessed?

No paper on the ethics of autonomous systems in the marine environment could be complete without a consideration of what we mean by ‘ethics’, and hence what we mean by ‘good’. Equally, we should explicitly consider *when* we should perform such an assessment. In their paper on the evaluation of the ethical use of Autonomous Robotic Systems in security applications, Christen *et al.* (2017) suggest that systems should be considered within their framework according to the degree that they demonstrated the following characteristics;

- Autarchy, or energetic independence

- Autonomy, or operational independence from human control
- Mobility
- Interaction with the Environment (which in their case included defensive systems)
- Learning; the capacity to change its behaviours

Such an analysis is pertinent as there has been a long history of the deployment of mobile, autonomous, environmentally interactive and energetically independent items in the sea. A passively drifting solar-powered sensor platform meets these criteria to varying degrees. We would suggest that the possibility for novel classes of impacts increases in proportion to the degree that an artefact displays these capacities, and especially in its behavioural autonomy and plasticity. Autonomy is only useful in that it helps an artefact better serve its intended purpose. Human control in some form or another is always required, and we should consider with particular care cases where there might be a long periods of autonomy, or where it is possible for novel behaviours to emerge through a combination of deterministic responses to a complex combination of environmental or mission factors, or through learning and adaptation.

5.5 Recommendations for NZOC

1. Each artefact will need ethical assessment, and this will be especially important where we expect high autonomy due to extended durations without human control or through behavioural plasticity.
2. This assessment should be based within an appropriate *ex ante* framework for ethical foresight analysis.
3. The ethical frame must be clearly determined, in order to justify the conclusions explicitly and in a manner that can be substantiated and supported. It may be necessary to consider other values of ‘good’ in a global endeavour.
4. This ethical frame should speak to the heart, for its success will depend upon this.

6. Summary

This report presents a rapid review of the literature on the ethics of marine robots in a research context, via summaries of ethics in marine research and AI, a mapping of specific ethical issues, and an examination of methods of reconciling or avoiding ethical hazard in this area.

As discussed in section 5, there are many ways to approach ethics. An ethical approach to marine research needs to involve a combination of working with existing research systems and developing new ones more focused on ethics. Deciding how best to act ethically is an important endeavour, and the decisions made now will frame our environment and development for years to come.

The implementation of ethics in this context also involves addressing and changing the research system. Scientists are variously aware of the social and ethical implications of their work and it may be the role of the science project manager or the institution’s ethics panel to guide researchers to consider these aspects and ensure that activities stay within ethical limits (Marsh & Kenchington, 2004). In a similar vein ethics, can be integrated into the project through deliverable elements of work packages and through training programmes for researchers. As the complexities of our interactions with the oceans become clearer, it may become more appropriate to dedicate complete work packages to ethics. For example, the ENVRIplus H2020 project dedicated a work package to developing an ethical framework for research infrastructure.

Getting an ethical case wrong not only risks reputational damage, and returns on invested funds, but also threatens the advancement and trust in the process of science and scientific endeavour itself.

Innovation and technology, including marine robots, have the potential to vastly improve data collection and sharing about the world's oceans. However, in order for the UK's marine research capability to move forward with confidence in the area of marine robots, there remain several aspects that need to be more deeply considered, examined and addressed: not least, the development of an appropriate ethical frame for emerging research endeavours.

Once such a frame is developed, it will allow the development of a set of robust ethical principles. Taking account of societal, environmental and design aspects, these would then help ensure that the UK maintains its world-leading position in marine research and innovation, and facilitates, encourages and supports the development of environmental, oceanographic research around the world.

7. References

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