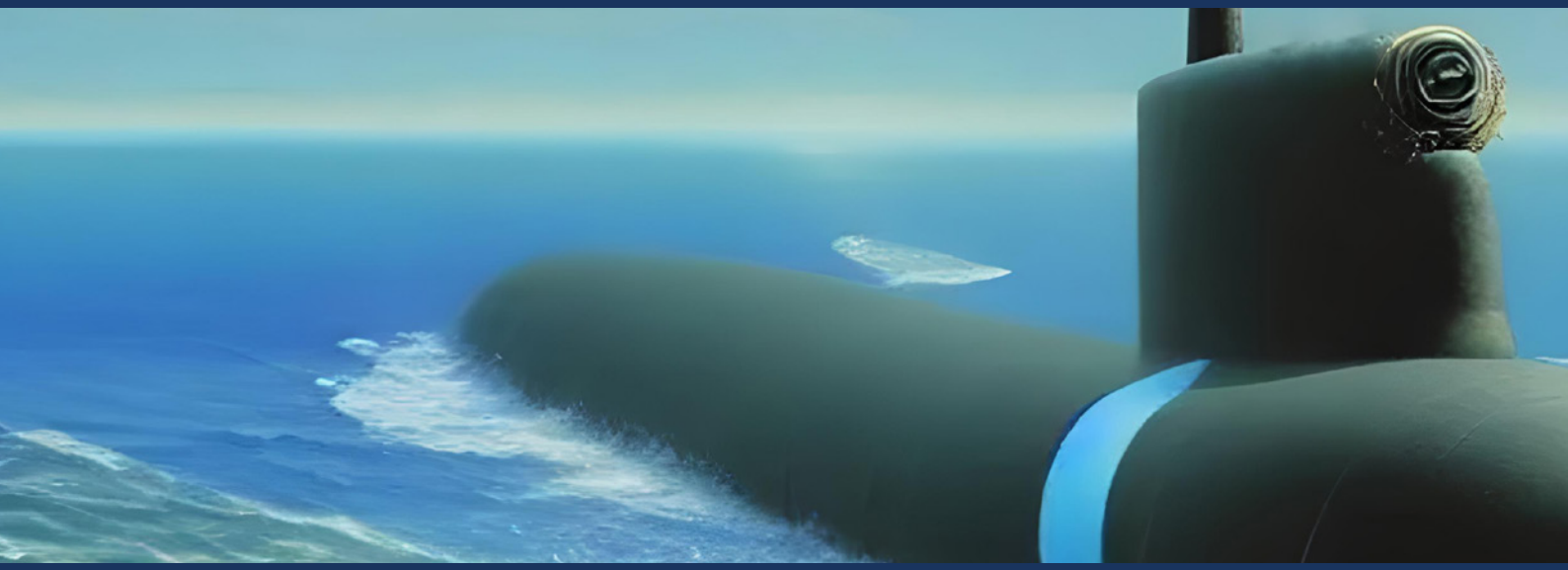


UNCREWED MARITIME SYSTEMS: A PRIMER

THEÒ BAJON & SARAH GRAND-CLÉMENT

SUMMARY OF KEY POINTS

- Uncrewed maritime systems (UMSs) be distinguished first by the environment in which they operate: on the surface of the water (uncrewed surface vehicles) or underneath it (uncrewed underwater vehicles, which can operate both on and under the surface). Within these two categorisations, UMSs can be distinguished according to characteristics such as their size, weight (or displacement), speed, range and, for underwater systems, depth. Generally, civilian UMSs tend to be smaller in size than military UMSs.
- Although their use in the military domain is currently limited, UMSs could pose significant international security challenges. Some of these are general maritime security challenges that are exacerbated by the use of UMSs, notably due to the maritime domain being vast and difficult to monitor. Other challenges are specific to UMSs, notably in terms of how the anticipated proliferation and misuse of these systems, particularly by non-state actors, will further affect overall security. Additionally, the lack of a legal definition for UMSs has been linked to uncertainty around the legality of their use for military activities in particular parts of the ocean.
- UMSs currently face specific technical challenges that limit their use and the performance of certain complex tasks. Research and innovation in this field, as well as in related areas, is likely to overcome these challenges by improving their navigation capabilities and their endurance. Developments in sensors, artificial intelligence and computational power will also improve autonomous navigation systems in maritime environments, thereby reducing the dependence on a crew.

INTRODUCTION

The development of uncrewed maritime systems (UMSs) – which include vehicles that can be piloted either remotely or semi-autonomously – has increased. The term UMS encompasses both the vehicle (the uncrewed maritime vehicle, UMV) and the control system that enables its remote operation. In the context of this primer, "autonomy" refers to the autonomy of a vehicle's navigation and object-identification functions enabled by artificial intelligence (AI), rather than the rules-based automation, or autonomy underlying the use of a vehicle's potentially lethal payload.

This primer is intended to provide policymakers, diplomats and other non-technical interested parties with an introductory overview of UMS technological developments and their security implications. Similar primers are also available on uncrewed aerial systems (UASs) and uncrewed ground systems (UGSs), as well as a compendium that gives an overview of all three systems and goes into further detail regarding areas of innovation related to these uncrewed systems. The primers and the compendium can also be used as technical guides on issues relating to uncrewed systems within frameworks and processes where such systems are relevant and are discussed, such as the Group of Governmental Experts (GGE) on the continuing operation and relevance of the United Nations Register of Conventional Arms (UNROCA) and its further development, the Conference of States Parties to the Arms Trade Treaty, and the GGE on Lethal Autonomous Weapons Systems.

This primer introduces the different types of UMS, describes their key components and functions, and outlines the main challenges that these systems can pose to international security. The focus of the primer is on describing the main areas of technological innovation and development related to the key components that comprise UMSs, outlining the anticipated areas of progress and potential concern. The material presented here is drawn from publicly available sources and from interviews with experts from the private sector, academia, national government, and regional or international organisations conducted between October 2021 and February 2022.

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DIFFERENT TYPES OF UMS

There is no universal classification of UMSs. UMSs, whether military or civilian, can first be differentiated according to the environment in which they operate:[1]

- **Surface:** UMSs that operate solely on the water surface.
- **Underwater:** UMSs that operate under and on the water surface.

Both surface and underwater systems can then be further differentiated by characteristics pertaining to their technical capabilities, such as their range, depth, endurance, payload capacity, size, speed and weight (also known as displacement), and whether they are armed or not.[2] While both types of system can be differentiated between small, medium and large systems, generally based on length and displacement, underwater systems are also differentiated in terms of the maximum depth at which they can operate and whether or not they are tethered.[3]

There are also differences between civilian and military UMSs. The size and capabilities such as power, endurance and speed of military UMSs have traditionally been greater than those of civilian UMSs. However, the increasing role played by the private sector in developing such systems for commercial purposes means that differences in capabilities are reducing.[4]

While there are different types of UMS, overall such systems also share certain characteristics with crewed systems, while retaining certain specificities, as explained in box 1.

Box 1: Differentiating between crewed and uncrewed systems

Crewed and uncrewed systems not only perform the same functions, but both have many similar characteristics. These include the structural components (e.g., the locomotion type, whereby both crewed and uncrewed systems can be surface or underwater vehicles) and the type of technology used to power and navigate these systems. Some of the technologies and areas of innovation that pertain to uncrewed systems can also apply to crewed systems – and vice versa. The main differences relate to the fact the crewed vessels have crew on board, unlike UMVs, which have no one on board. While the vehicle may be uncrewed, as long as it is not fully autonomous, there are operators controlling some or all of its functions.

The distance and means through which a UMS can be operated and what inputs are needed from the UMS operator vary depending on the type of system, its complexity, and whether it is a military or civilian system. In a remotely controlled UMS, an operator retains control of the navigation of the system and responds to the information provided by the system's sensors. However, there is ongoing research seeking to autonomise navigation through technological innovations in domains relating to communications and AI, to name but a few, in order to further reduce or even remove the role of human operators.

There are additional differences related to whether a maritime platform has someone onboard. Some are physical: for example, without an operator and crew in the vehicle, space becomes available for other features or payload. Additionally, the risk to the life of the UMV operator is lowered or even removed compared to that of a crewed vessel if attacked. Another difference relates to the types of task that crewed and uncrewed systems can undertake. For example, uncrewed systems can be used for more dangerous activities, such as minesweeping and activities requiring more depth of operation, as well as for longer-duration missions.



1 Veal et al. (2019).
2 Manley (2016); Martin (2013); Martin et al. (2019).
3 A tethered UMS means that there is a physical connection between the vehicle and the remote-control system.
4 Cheng & Zhang (2018).

FUNCTIONS OF A UMS

Surface and underwater UMSs perform similar tasks and functions, and both can undertake a range of tasks across both the civilian and military domains.[5]

Figure 1 displays the functions of UMSs that are solely military and solely civilian, as well as functions shared across both domains, without differentiating between surface and underwater systems.

Given that there are some areas of overlap for the functions undertaken by military and civilian UMS, differences between the systems focus particularly on the technical capabilities of the systems as well as the environment in which they operate.

Figure 1: Functions of UMSs in the military and civilian domains

Military functions	Military and civilian functions	Civilian functions
> Defensive actions (e.g., mine countermeasures) > Strike operations (if armed) > Tapping or disrupting underwater communications cables > Area/sea denial	> Logistics (e.g., resupplying, goods delivery) > Search and rescue > Law enforcement support (e.g., fisheries or maritime border surveillance) > Monitoring and intelligence, surveillance, reconnaissance	> Commercial use > Hobbyist > Scientific research

CURRENT CHALLENGES TO INTERNATIONAL SECURITY

UMSs can provide a strategic advantage in the maritime domain. Conventional crewed systems are already hard to detect given the vast and difficult to monitor environment in which they operate. This problem is compounded by the fact it can be difficult to differentiate between crewed and uncrewed systems.[6] Additionally, while UMSs are not necessarily currently accessible to a large number of actors, and nor are they available in large numbers, the development and use of UMSs is increasing, particularly as the maritime domain facilitates the use of uncrewed systems given that it is regarded as relatively "uncluttered" and "uncomplicated".[7] The following is a non-exhaustive list of challenges to international security posed by UMSs:

- **Proliferation and misuse:** UMSs have undergone significant development over the last two decades due to technological advances, which has enabled an increased uncrewed presence in the maritime domain. This has been combined with a reduction in the cost of systems and their components, thus increasing the possibility that these systems will be accessible to a larger number of actors (military and civilian, state and non-state), albeit with a wide difference in levels of performance between systems.[8] In parallel, there will be increased use of such systems for illicit activity, such as to aid with the transport of illicit goods, or by armed non-state actors, such as terrorist groups and pirates, to conduct surveillance or even attacks, should systems be weaponised.[9]

  Despite increased access to advanced technology, it should nonetheless be noted that there exists and will continue to exist a significant divergence in terms of the technology used across different systems, ranging from very high-end to very low-end systems.

- **Change to the threshold for the use of force:** The use and proliferation of UMSs by military actors could change the way in which force is used in the maritime domain, notably by lowering the threshold for the use of force, particularly from the point of view of the legitimate use of force and its definition in international law. Additionally, the ability of UMSs to remove personnel from risk could lead to an intensified maritime presence and could incentivise armed hostilities or conflict.[10]

- **Identification of UMS posing a security threat:** Technological advances are increasingly blurring the lines between military and civilian technologies. It can be difficult to differentiate between certain military and civilian systems once in operation, meaning that it can be challenging to assess which systems pose a military threat and which do not. Threats may, for example, take the form of offensive backdoor cyber activities, destruction of underwater communication cables or the physical use of the system itself against a target (e.g., blocking the propellers of a submarine or a ship). It can also be difficult to detect UMSs at all, due to technological innovations that seek to improve the stealth of these systems, such as through designs conceived to mimic aquatic creatures and the use of materials that lower a system's electromagnetic signatures.[11]

5 Chang et al. (2020).
6 Matos et al. (2017).
7 UNIDIR (2015).
8 Omitola et al. (2018).
9 Chadwick (2020); Dinstein & Dahl (2020).
10 Aliferis (2021).
11 Heintschel von Heinegg (2018).

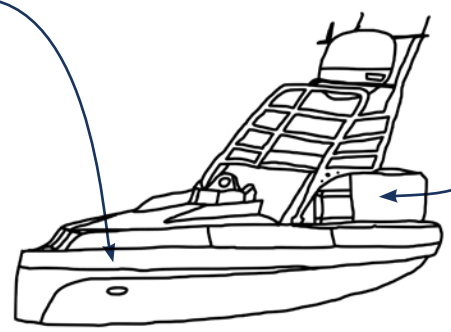
- **Use of non-offensive systems to carry out attacks against infrastructure:** Some types of UMS that are not designed to conduct offensive activities can be used to conduct tasks and activities that can cause damage, whether material or not. Beyond lethal attacks, these initially non-offensive systems or components can target civilian or dual-use infrastructure.[12]
- **Ethical and legal challenges:** The use of UMSs for lethal purposes can pose challenges to the interpretation and application of international humanitarian law and international human rights law, particularly if used without proper constraints or outside a conflict. In broader international law, while the use of UMSs is governed by the United Nations Convention on the Law of the Sea (UNCLOS), there are ongoing challenges and uncertainty around the legality of the use of such systems for military activities, particularly in the exclusive economic zones of coastal states.[13] This is particularly the case for dual-use systems whose ultimate purpose can remain unclear.[14]
- **Exploitation of system vulnerabilities:** UMSs, particularly surface systems, are also vulnerable to interference, such as by jamming, spoofing, hacking, or otherwise disrupting the data links between remotely piloted vehicles and their operators. Lack of cybersecurity protection can compromise the data collected through misappropriation (theft), data corruption or simply deletion.[15]

KEY COMPONENTS OF A UMS

Most UMSs have three main components: the vehicle structure, the payload and the remote-control system (illustrated in Figure 2). Each is comprised of a number of sub-components.

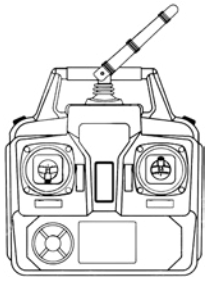
Figure 2: Key components of a UMS

The **vehicle structure** includes a number of essential sub-components which are necessary to enable the system to operate or to fulfil its intended functions. This notably includes the vehicle frame, structure and material; the power source and means of propulsion; the communication system; and the electronics and sensors. The latter two sub-components enable communication between the UMS and the remote-control system.



The **payload** refers to additional components which can be carried by the UMS but are not essential to its operability. Both civilian and military vehicles can incorporate a payload. This can include additional sensors (beyond those needed for navigation), goods (e.g., medical supplies or food), or weapon systems.

The **remote-control system** refers to the communications with the system and its remote navigation. The remote-control system can vary in complexity depending on the type of UMS and its level of navigational autonomy, but generally includes an operator and wider crew; an interface to communicate with the system; and a communications link, the complexity of which can vary depending on the user.



(image provided for illustrative purposes only)

AREAS OF INNOVATION

UMSs continue to face several technical challenges that have constrained, to some extent, their use on a wider scale. These technical challenges are the focus of ongoing research and innovation, which is seeking to create even more capable systems. The main technical challenges faced by UMSs currently include the ability to communicate in real time with the control centre, particularly for underwater systems; long-term power supply; and reliable autonomy that would allow a system to remain operational and on-mission for long periods of time.

The technological innovations outlined below include developments that are specific to UMSs as well as those that apply to uncrewed systems in general. Additionally, while some of the technologies discussed below are already under development and in some cases in limited use in the most advanced military systems, others are still nascent.

12 Schmitt & Goddard (2016).
13 McKenzie (2021).
14 Chang et al. (2020).
15 Silverajan et al. (2018).

Vehicle shape, structure and material

The vehicle frame encompasses the "skeleton" of the UMS, meaning the hardware comprising the body of the system. Of particular importance here is the categorisation of systems according to their domain (i.e., air, ground or maritime), as is the case within arms control processes. These may become outdated in the future as a result of innovations regarding cross-domain capabilities.

The main areas of innovation include:

- **Vehicle structure:** Research is ongoing regarding improvement of vehicle structures to make UMVs even more difficult to detect. For example, there are both recent and emerging innovations in the structural shapes of both surface and underwater UMVs in order to allow them to be stealthier and to avoid not only visual but also electro-acoustic detection.[16] Such advances often use biomimicry, where synthetic products or systems are modelled on biological systems, whereby the vehicle structure seeks to mimic that of aquatic creatures.[17]
- **Cross-domain systems:** There are developments enabling UMSs to operate across the land, sea and air domains. This involves, for example, adaptation of their frame and structure, as is the case with amphibious vehicles, which are able to move on land and water, or vehicles that are able to navigate both over and under water.[18] There is also research on developing systems that can fly and move on or under water.[19]
- **Advanced materials:** Research is seeking to develop advanced materials which comprise the structure or frame, or coat the structure of a UMV. For example, the following areas are being explored:
  - Materials with improved waterproof capacity and performance to protect the system's water-sensitive components,[20]
  - Materials that can provide improved hydrodynamics to help UMVs move more rapidly,[21] and
  - Materials that improve the potential for buoyancy or the ability to be submersible, depending on whether the UMS is a surface or underwater system.[22]

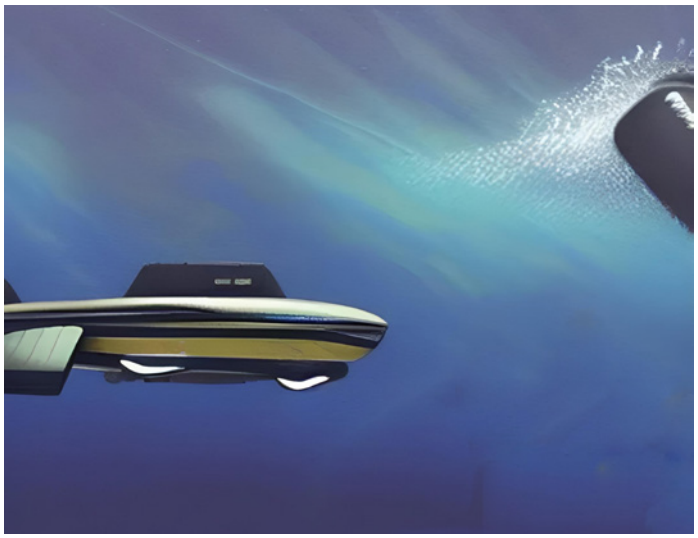
Overall, application of advanced materials to UMSs aims to create sturdier and more enduring systems, as well as systems that can reach greater depths.

Power source and means of propulsion

A UMV can be powered by, for example, fuel or by renewable energy. Of particular importance here is that innovations aim to further improve the endurance of UMSs, for longer operation times. Improved endurance can make the use of UMSs more appealing, which could have an impact on international security if used for illegal or harmful purposes.

The main areas of innovation include:

- **Battery advances:** One of the limitations of battery-powered UMVs is their endurance. Lithium batteries are the most commonly used today. However, there is research regarding the specific use of batteries in a maritime environment, with a focus on improving waterproof batteries.[23] Battery advances would enable increased endurance of UMVs, in particular those that are battery-powered, as well as the endurance of the electronics embedded within these systems. Higher endurance means that a UMS could be operational for longer periods of time.
- **Hydrogen–oxygen fuel cells:** Compressed hydrogen gas and liquid hydrogen fuel cells enable UMSs to navigate greater distances, while enabling greater energy-storage capabilities. The technology behind compressed hydrogen remains more mature than that of liquid hydrogen, although research is ongoing to make both viable solutions.
- **Other types of power source and propulsion method:** Use of solar power, either on its own or alongside other propulsions systems (e.g., batteries, fuel cells or internal combustion engines) can enable long-term persistent sailing for surface UMVs. There is ongoing innovation in solar cell technology as well as research to leverage the mechanical energy of marine currents and waves, with the latest innovation demonstrating increasingly high energy yields.[24] While helical propulsion is the most commonly used propulsion system for UMVs, other types of propulsion movement inspired by animals, and in particular cephalopods, are being trialled in order to further optimise the hydrodynamics of movements, while optimising energy consumption and movement, again with the aim of enabling greater endurance of UMSs.[25]



16 Gerigk (2016).
17 Olsen et al. (2020).
18 Vijayanandh et al. (2019); Costanzi et all (2019).
19 Yang et al. (2015).
20 Tomków et al. (2020).
21 Gerigk & Wójtowicz (2015).
22 Blintsov & Klochkov (2019).
23 Budiyono (2009).
24 Clemente et al. (2021).
25 Luo et al. (2020).

Communication system

The communication system encompasses all relevant elements that link the UMV and its operator. Of importance here is that innovations strengthen the link between the UMV and the remote-control system, also helping to ensure better data connectivity between the vehicle and the operator, as well as enabling greater distance between them.

The main areas of innovation linked to this component are:

- **Radio frequency communication technology:** Although not the preferred form of communication, due to the technical constraints of the maritime environment, innovations in cellular data transmission and connectivity allow for potentially higher rates of data transfer, even potentially in the underwater environment. The depth of operation may limit these types of communications for underwater systems.[26] There has also been research on using software-defined cognitive radios through cooperative cognitive maritime big data systems. These radios aim to use the available radio frequency (RF) spectrum more effectively, overcome the competition in certain RFs due to an increasing number of electronic devices using such frequencies, and overall increase the resilience of RF communications. UMSs can serve as relays in these networks or directly benefit from them.[27]
- **Satellite communications:** While satellite coverage is not homogenous across all maritime areas, surface UMSs can nonetheless use satellite networks to a certain extent in order to receive and transmit information. Several innovations in the field seek to continue to improve the accuracy and speed of signals.[28]
- **Hydroacoustic communication:** In recent years, there have been advances and innovations in the field of hydroacoustic communication, which is the transmission of information through sound underwater. In particular, advances have been made in terms of transmitting information by filtering out noise from the maritime environment.[29]
- **Antenna innovations:** Novel antenna designs and ongoing innovations around different antenna types, such as to increase signal strength, are being researched and integrated into systems, particularly high-speed surface UMSs.[30] Used to transmit and receive data, antennas can be critical for certain types of UMS, particularly those that do not integrate autonomous navigation features.

Electronics and sensors

The electronic elements and sensors embedded in a UMS enable it to perform functions such as navigation and decision-making. Of particular importance here is research seeking to ensure that UMVs can increasingly navigate autonomously. This reduces, or may even completely remove, the role of the remote operator, thus increasingly removing human control while also enabling UMVs to function autonomously and for long periods of time.

In the case of electronics and sensors for guidance, navigation and control, the main areas of innovation include:

- **Global navigation satellite system (GNSS):** Continuous improvement in satellite technology and an expected increase in the number of satellites will improve the accuracy of positioning of surface UMVs and thus the precision of their navigation.[31] Technological advances in this area include the ability of some UMSs to pick up and exploit extremely low-level GNSS signals and the ability of underwater UMSs to navigate using this technology.
- **Hydroacoustic navigation:** The transmission and reception of electro- or hydroacoustic waves provides a UMS with a modelled map of its environment and surroundings and thus nables it to navigate. This is particularly important for underwater systems, but also has applicability to surface systems. Several innovations seek to enable a wider range of hydroacoustic navigation systems as well as an increased accuracy in measurements and object recognition. This, for example, includes enabling the recognition of the type of object and the material it is made of, not only its existence.[32]
- **Inertial navigation system:** The inertial navigation system (INS), which includes an inertial measurement unit measuring the speed, rotation and position of a system and a computational unit, is a core aspect enabling navigation for UMSs, as it does not rely on an external element, such as satellite data.[33] Research has sought to increase the accuracy of measurements and data processing of INS on surface and underwater UMSs. Furthermore, the accuracy of INS can also be complemented by the use of high-precision cameras.[34]
- **Sensor improvements for navigation:** Sensors can capture data on their surroundings and play a critical role for navigation and decision-making by a system. They are key in areas with no GNSS signals. Along with AI and computing power, a range of sensors aid the navigation of UMSs, with some slight differences between surface and underwater systems in the specific types of sensor used. There is also research seeking to develop and improve sensors to ensure redundancy, higher resolution data collection and more accuracy for navigational purposes.

26 Wu et al. (2017).
27 Yang et al. (2018).
28 Zolich et al. (2019).
29 Kozhemyakin et al. (2018).
30 Khosravi et al. (2019).
31 Yong Ko et al. (2016).
32 Jones et al. (2013).
33 Bao et al. (2020).
34 Sahoo et al. (2019).

In the case of electronics and sensors for sensing, perception and autonomy, the main areas of innovation include:

- **Sensor improvements:** Advances in the sensors as described above are also applicable to a system's wider perception and autonomy. Sensor data, combined with information such as location coordinates and text-based descriptions, is another area of research aiming to improve the ability of a UMV to perceive and therefore respond to its environment with limited operator input.
- **Artificial intelligence:** Using data obtained from the various sensors, AI can aid or even directly undertake decision-making in relation to a range of tasks, such as navigation (e.g., mapping routes and collision avoidance) and surveillance (e.g., object recognition and tracking). Advances continue, aided by the growth in computing power as well as the amount of data available to use for training. As AI algorithms continue to improve along with sensor data, this will help improve the ability of UMVs to autonomously navigate, including without the need to rely on GNSS.[35] Currently, AI approaches using behaviour trees (i.e., a way to plan the execution of a task in robotics) are used in the maritime domain to enable autonomous behaviour. This allows vehicles to respond to their environment while pursuing their intended outcome, thus enabling limited human involvement during a mission. Developments include strengthening these approaches to enhance the ability for a UMS to operate more intelligently within its environment and with regard to other systems.
- **Computing power:** Semiconductors, or chips, are the basis of computing power. There have been continuous advances in this domain to make chips smaller yet more powerful, while consuming less power. With AI on chips, the AI is embedded in specifically created chips. Given that the use of AI is highly interlinked to computing power, AI on chips enables the level and speed of operations required by the AI and reduces even further reliance on the operator.

Box 2 describes other broader areas of technological progress that have an impact on UMSs as well as other types of uncrewed system.

Box 2: Additional areas of innovation

Electronics and components of all types are **becoming increasingly miniaturised**, simultaneously becoming more powerful and, in some cases, cheaper.[36] This includes, for example, making smaller chips and sensors but also smaller propulsion solutions, such as fuel cells, driven by innovations in the field of nanotechnology, such as nanomaterials. This trend means that smaller systems may be just as smart and capable as larger ones, whereby size is no longer an indication of capability. This may have an impact on arms control categorisations.

While the use of **quantum technology** in everyday occurrences still remains a rather distant possibility, its various uses are expected to lead to vast changes. For example, quantum computing will greatly increase the speed of data processing. Quantum communications (i.e., quantum key distribution) is expected to create secure channels of communication as well as enable a higher level of encryption and decryption.[37] Quantum sensors would, for example, remove the need to rely on GNSS for navigation.[38]

CONCLUDING REMARKS

Surface and underwater uncrewed maritime systems have a wide range of application areas. There appears to be a growing interest by both state and non-state actors in the development and use of these systems, not least due to the strategic interest of the maritime domain. The areas of innovation and research outlined above are likely to see significant future evolution, albeit with distinctions in objectives and application between military and civilian systems. Overall, increased stealth, improved endurance, more reliable communications and, in particular, more navigational autonomy linked to GNSS, sensors and AI will lead to increased use of and reliance on such systems, with an impact on conventional arms control as well as international security.

The predictable increase in the use of these systems across a range of applications, involving different types of innovation, poses several challenges to international security. Notably, an intensification and diversification of use of UMSs is foreseeable, notably in terms of the use of these systems by non-state actors, whereas their development and use have so far been limited to state actors and, to a more limited extent to date, private commercial ventures. Thus, technological advances in UMSs can pose different types of security challenge in terms of control of these developments and innovations, notably regarding the possibility of restricting the access to certain technologies to malicious actors.

35 Interview with David Scaramuzza (27/10/2021).
36 Interviews with Geert de Cubber (27/10/2021), Chief Engineer, Trusted Autonomous Systems (21/12/2021); anonymous interviewee D (15/12/2021).
37 Interviews with anonymous interviewees I and J (01/02/1991).
38 Tucker (2021); Interview with Chief Engineer, Trusted Autonomous Systems (21/12/2021).

RESEARCH INTERVIEWS

We are grateful to all the experts who took part in the research interviews and for the information they contributed; the experts cited in this report are provided below.

Designation or name	Affiliation	Interview date
David Scaramuzza	University of Zurich	22 October 2021
Geert de Cubber	Belgian Royal Military Academy	27 October 2021
Interviewee D	–	15 December 2021
Chief Engineer	Trusted Autonomous Systems	21 December 2021
Interviewee I	–	1 February 2022
Interviewee J	–	1 February 2022





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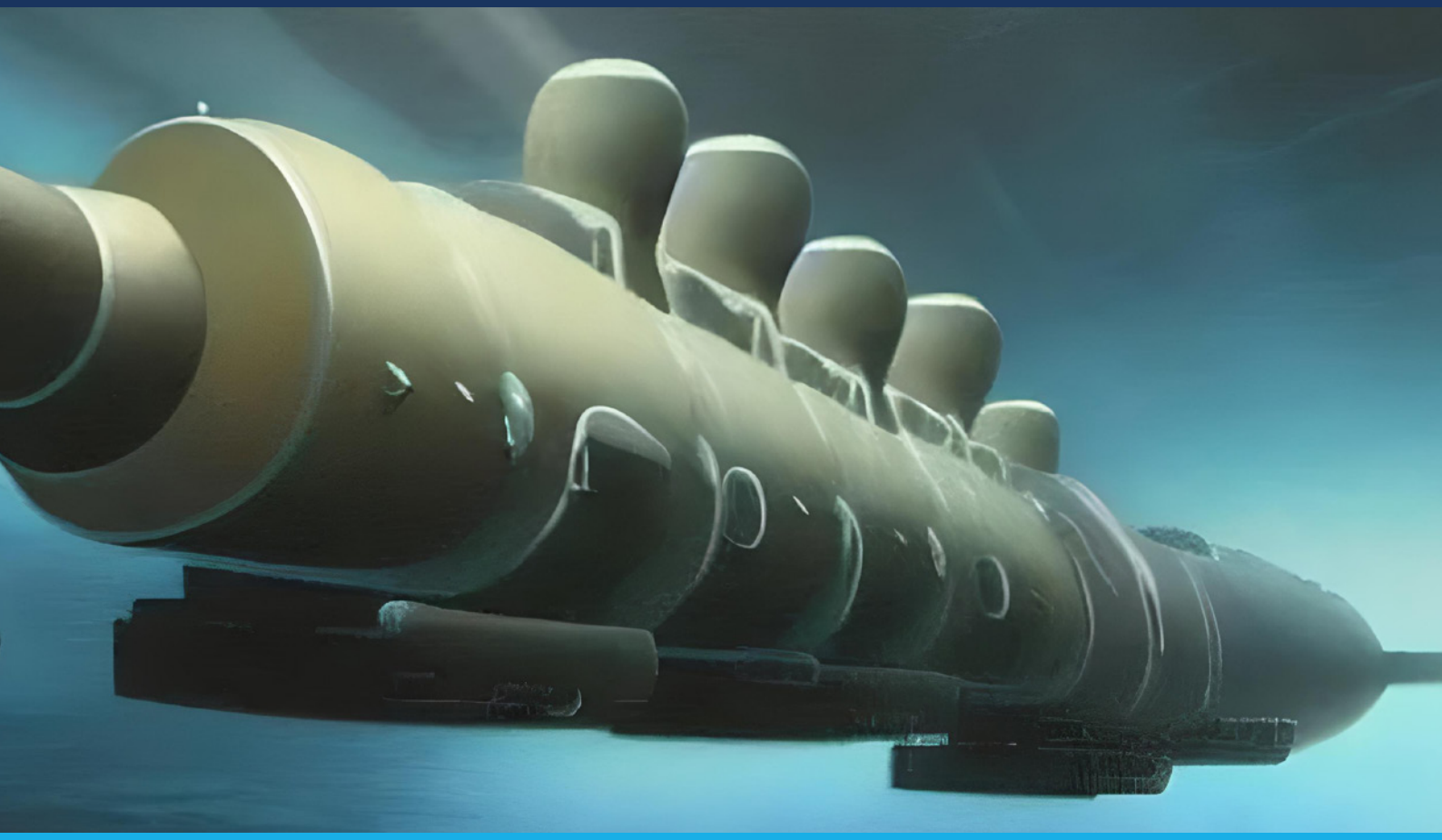
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