UNCREWED AERIAL, GROUND, AND MARITIME SYSTEMS: A COMPENDIUM

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EXECUTIVE SUMMARY

Uncrewed systems include uncrewed aerial systems (UASs), uncrewed ground systems (UGSs) and uncrewed maritime systems (UMSs). In recent years, the development and use of UASs has increased, and progress to advance UMSs has also been made.

While the uncrewed systems of each of the three domains vary in specifications and capabilities – for example, some UMSs operate on the surface while others navigate underwater, and some UASs have fixed-wings while others have rotary-wings – all three types have military and civilian applications. Overall, uncrewed systems intended for use by the military tend to have a higher technical performance then systems intended for civilian uses, such as better endurance and payload capacity. However, the functions undertaken by uncrewed aerial, ground and maritime systems demonstrate that many systems are dual-use, that is, many military tasks could equally be undertaken by civilian systems and vice versa. Moreover, given the similarities across the civilian and military sectors in functions undertaken by uncrewed systems, it is likely that advances in uncrewed systems intended for one sector will be transferrable, to a large extent, to those operating in the other.

Uncrewed systems across all three domains pose challenges to international security. However, the scope and scale of the challenges differ depending on the system. For example, while all systems pose proliferation and misuse challenges, these are currently more acute regarding UASs than UMSs and UGSs. This is due to UASs being the most-used systems to-date given their widespread use in both the civilian and military sectors, and the accessibility of the aerial domain to a wide range of actors. While UMSs are not necessarily currently accessible to as many actors as UASs, and nor are they available in as large numbers, their development and use is increasing. Compared to UASs and UMSs, UGSs pose fewer threats to international security given that they are less developed and, thus, their use has been limited to specific areas or for specific activities. There is, nonetheless, an increased interest in developing UGSs that can navigate autonomously and are armed.

Each type of system is also faced with certain technical challenges specific to its domain of operation that limit its performance. One of the main technical challenges affecting all systems relates to endurance. Yet, enabling technologies that are common to all systems are addressing many of these challenges. These include developments in advanced materials, power sources and propulsion, sensors, artificial intelligence, and computing power. Advances applicable to an uncrewed system currently operating in one domain may be transferable and are likely to apply in other domains too. At the same time, there are likely to be differences between how these may be integrated within civilian or military models.

Overall, the enabling technologies used in uncrewed systems are likely to become ever more similar. Advances to one type of uncrewed system may thus be transferrable to any other type, with uncrewed systems as a whole posing an increased threat to international peace and security.

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GLOSSARY

Acoustic signature	The ability to detect a system by the noise it generates
Biomimicry	The modelling of synthetic products or systems on biological systems, enabling them to have similar or equal properties
Cognitive radio	Radios which select the most appropriate channel automatically, in contrast to regular radios which have a defined frequency and need to be changed manually
Electromagnetic signature	The ability to detect a system by the ray or wave it emits
Electromagnetic spectrum	The range of frequencies or wavelengths, which form different types of ray or wave including x-rays, visible light, infrared waves, microwaves, radio waves, etc., the latter of which is used for cell phone and radio communication
Energy density	The amount of energy which is stored in a battery in comparison to its weight; a battery with greater energy density will therefore perform better and have greater endurance
Hacking	Attempts to exploit and identify weaknesses in digital devices in order to gain unauthorized access
Infrared	A type of wavelength that is invisible to the human eye but is emitted by warm or hot objects (or people); infrared vision refers to the ability to detect heat sources at night-time
Jamming	The blocking or interference of wireless communications, of which radio waves
Morphing	The ability of a non-biological system to change and adapt its shape or structure
Robotic teaming	The ability of robotic systems to collaborate to complete a task via centralized control, whereby each robot is controlled by a separate operator; distinct from swarming
Spoofing	A way of gaining the trust of an individual in the digital sphere through a fake or disguised identify
Stealth	The ability of a non-biological system to avoid or reduce its detection by sensors
Supercapacitor	A device which has a lower energy density than batteries, but with a higher power density, meaning it can store and release more short-term power

ABBREVIATIONS

AI	Artificial intelligence
GGE	Group of Governmental Experts
GNSS	Global navigation satellite system
IED	Improvised explosive device
INS	Inertial navigation system
RF	Radiofrequency
SATCOM	Satellite communications
UAS	Uncrewed aerial system
UAV	Uncrewed aerial vehicle
UGS	Uncrewed ground system
UGV	Uncrewed ground vehicle
UMS	Uncrewed maritime system
UMV	Uncrewed maritime vehicle

1. INTRODUCTION

Uncrewed systems – which include vehicles that can be piloted either remotely or semi-autonomously – have developed remarkably. This is particularly the case for uncrewed aerial systems (UASs), but also increasingly for uncrewed maritime systems (UMSs) and uncrewed ground systems (UGSs). The term uncrewed system encompasses both the vehicle – the uncrewed aerial vehicle (UAV), uncrewed ground vehicle (UGV) or the uncrewed maritime vehicle (UMV) – and the control system that enables its remote operation. In the context of this paper, "autonomy" refers to the application of artificial intelligence (AI) to a vehicle's navigation and object-identification functions, rather than the rules-based automation or autonomy underlying the use of a vehicle's weapons and other potentially lethal payload.

This compendium is intended to provide policymakers, diplomats and other non-technical interested parties with an introductory overview and comparison of technological developments and their security implications relating to UASs, UGSs and UMSs. In 2022, UNIDIR released a primer for each of the three domains in which uncrewed systems operate.[1] While each primer gives an in-depth introduction into each type of uncrewed system, this compendium provides a comparative overview that highlights the common developments and security implications of these systems, as well as what distinguishes them. The compendium and the primers also serve as technical guides on issues relating to uncrewed systems for use within frameworks and processes where such systems are relevant and 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 compendium introduces the different types of uncrewed system (section 2), describes their main functions (section 3), and outlines similarities and differences related to the main challenges that these systems can pose to international security (section 4). The compendium also describes the key components that comprise uncrewed systems (section 5) and the main areas of technological innovation and development related to these, outlining the anticipated areas of progress and potential concern, as well as areas of overlap between key enabling technology across the three types of systems (section 6). The material presented here is drawn from publicly available sources and from interviews with experts from the private sector, academia, national government, and regional and international organisations conducted between October 2021 and February 2022.

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[1] The primers can be found at https://unidir.org/publication/uncrewed-aerial-systems-primer, https://unidir.org/publication/uncrewed-ground-systems-primer and https://unidir.org/publication/uncrewed-maritime-systems-primer.

2. DIFFERENTIATING THE VARIOUS TYPES OF UNCREWED SYSTEMS

Different types of UAS, UMS and UGS are currently in use. Uncrewed systems of all types are primarily differentiated according to their technical characteristics, such as their endurance, weight, or payload capacity. Such characteristics are also often used to categorise these systems.[2] Other characteristics that can be used to differentiate uncrewed systems include wing type (UASs), locomotion (UGSs) and environment of operation (UMSs), as outlined in table 1.

Table 1: Overview of different types of UAS, UGS and UMS based on wing type, locomotion, and environment of operation

UAS: Wing type [3]	UGS: Locomotion	UMS: Environment of operation
Rotary-wing: These systems can have one, four, six or more rotors. Compared to fixed-wing systems, they can launch and land more easily in a limited space and are more manoeuvrable, but also consume and require more energy. **Fixed-wing:** Compared to rotary-wing systems, fixed-wing UASs can carry heavier payloads, are able to loiter for longer periods of time, and can operate over a significantly greater range for a given take-off weight. **Other:** Other wing types exist, including hybrid systems, which combine both fixed- and rotary-wings, and flapping-wing systems, which mimic bird or insect wings. However, the use of hybrid and flapping-wing systems remains limited in both the civilian and military sectors.	**Wheeled:** Wheels are the most power-efficient locomotion type. However, wheels are less suited for off-road terrain than tracked vehicles. These vehicles can carry substantial firepower. **Tracked:** Tracks are well suited for use off-road but consume more power and operate at lower speeds than wheeled vehicles. As with wheeled systems, tracked vehicles can carry substantial firepower. **Legged:** Legged systems can manoeuvre rough terrain well. However, they are generally slower and require more power than either wheels or tracks. They are also mechanically complex due to their need for balance and stability. Unlike wheeled and tracked systems, which can come in a variety of sizes, current legged systems tend to be small. As such, compared to large armed wheeled or tracked systems, armed legged systems are only able to carry smaller weapons, such as adapted small arms.	**Surface:** UMSs that operate solely on the water surface. **Underwater:** UMSs that operate under and on the water surface.

3. FUNCTIONS OF UNCREWED SYSTEMS

Uncrewed systems in all domains are being developed and used for military and civilian use. Many of these systems have a dual-use nature – in other words, they can have both a military and a civilian application. However, while there are similarities in functions undertaken by military and civilian uncrewed systems, their technical capabilities differ. The technical characteristics and capabilities of military systems have traditionally been perceived as greater than those of civilian systems. For example, a purely military UAS or UGS would be expected to have a greater endurance, to be able to carry more payload, and to incorporate higher-end technology than a system that is aimed at hobbyist use. However, the increasing role played by the private sector in developing such systems for commercial purposes means that differences in capabilities are reducing.[4]

Furthermore, there are similarities in functions undertaken by systems operating across sectors, such as for logistics or monitoring, intelligence, surveillance and reconnaissance. Given that there are similarities in the technology enabling such tasks – such as means of propulsion, sensors, and AI – it is likely that advances pertaining to one type of uncrewed system will be transferrable, to a large extent, to others operating in other sectors. Figure 2 displays the functions of uncrewed systems – across UASs, UGSs and UMSs – that are solely military and solely civilian, as well as functions shared across both sectors.

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[2] There is no universal classification based on these characteristics. For example, the United States divides military UASs into five groups according to their take-off weight, operating altitude, and airspeed. See UAS Task Force Airspace Integration Integrated Product Team (2011). In contrast, the North Atlantic Treaty Organization (NATO) divides UASs into three classes, based on weight.

[3] This is currently how UASs are distinguished within the categories of UNROCA. Following the 2016 GGE, UNROCA distinguishes between crewed and uncrewed fixed-wing systems. A similar distinction for rotary-wing systems was recommended following the 2022 GGE.

[4] Cheng & Zhang (2018).

Figure 1: *Functions of UASs in the military and civilian domains*[5]

Military functions	Military and civilian fuctions	Civilian fuctions
○ 🟢 ● Strike operations (if armed)	○ 🟢 ● Logistics and logistical support	○ 🟢 ● Hobbyist
○ 🟢 ● Target acquisition	○ 🟢 ● Monitoring, intelligence, surveillance and reconnaissance	○ 🟢 ● Commercial use
○ 🟢 Chemical, biological, radiological and nuclear detection	○ 🟢 ● Search and rescue	○ 🟢 ● Scientific research
🟢 ● Weapon detection and disposal (e.g., mine clearing and IED search-and-destroy)	○ 🟢 ● Law enforcement support	
🟢 Supporting platform (e.g., provision of power to uncrewed aerial systems, communication relay)	○ Communication and data relay	
● Tapping or disrupting underwater commuications cables		
● Area/sea denial		

○ UAS 🟢 UGS ● UMS

While it is important to recognised differences between types of uncrewed system, it is also important to recognise how crewed and uncrewed systems differ, and why this is important, as outlined in box 1.

Box 1: Differentiating between crewed and uncrewed systems

Crewed and uncrewed systems can perform the same functions and have many similar characteristics. These include the structural components (e.g., both crewed and uncrewed vehicles can have rotors or fixed wings in the case of aerial systems, can be wheeled or tracked in the case of ground systems, and operate on the surface or underwater in the case of maritime systems) and the type of technology used to power and navigate these systems. Some of the technologies and areas of innovation applied to uncrewed systems can also apply to crewed systems – and vice versa.

The main differences relate to the fact that crewed vehicles have a pilot, driver or crew on board, unlike uncrewed systems, which have no one on board. Other differences arise from this distinction, as outlined below.

While a vehicle may be uncrewed, as long as it is not fully autonomous there are human operators controlling some or all of its functions. The distance and means through which an uncrewed system can be operated and what inputs are needed from the operator vary depending on the type of system, its complexity, and whether it is a military or civilian system. In a remotely controlled uncrewed system, an operator retains control of the navigation of the system and responds to the information provided by the system's sensors. However, ongoing research is seeking to autonomise navigation through technological innovations in areas relating to communications and AI, among others, in order to further reduce or even remove the role of human operators.

Additional differences relate to whether an aerial, ground or maritime platform has someone onboard. Some are physical: for example, without a pilot, driver or crew inside a vehicle, size is no longer an issue, and uncrewed vehicles can be smaller than their crewed alternatives or can carry a payload in place of the crewed elements.

Additionally, the risk to life is lowered with uncrewed systems. While the pilot, driver or navigator of a crewed system is in the frontline should their vehicle be attacked, the risk to the remote operator (if there is one) of an uncrewed system is lowered or even removed given their distance from the vehicle.

In turn, this affects the tasks that crewed and uncrewed systems will undertake. For example, compared to their crewed counterparts, UGSs can be used for more dangerous activities (e.g., demining and dealing with improvised explosive devices (IEDs)), while UMSs can undertake activities at a greater depth, as well as longer-duration missions.

However, an uncrewed system is also more reliant on sensors and on communications networks for contact with its operator. These electronic elements all operate within the electromagnetic spectrum. As such, uncrewed systems are more susceptible to jamming (i.e., interference with its electronics via the electromagnetic spectrum) as there is no crew onboard to take manual control of the system.

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[5] Given that surface and underwater UMSs perform similar tasks and functions, the figure does not differentiate between these.

4. CURRENT CHALLENGES TO INTERNATIONAL SECURITY

Uncrewed systems pose challenges specific to their domain of operation, as well as challenges common to all systems. The following, non-exhaustive overview of these challenges includes proliferation, misuse and exploitation of vulnerabilities, differentiation of military versus civilian systems, and ability to identify systems.

CROSS-CUTTING CHALLENGES

PROLIFERATION

The **increased accessibility and use of uncrewed systems** is a particular challenge in the aerial domain, but also increasingly in the maritime and ground domains. Several factors facilitate access, notably lower costs than crewed systems, ease of use, the accessibility and affordability of the components and, increasingly, the application of advanced technology. This has increased the possibility that these systems will be accessible to a greater number of actors (military and civilian, state and non-state). Despite greater 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 within each domain, ranging from very high-end to very low-end systems.[6]

MISUSE

Democratisation of access to uncrewed systems, which increases the probability of their diversion from their original intended use, can **lead to them being used in illicit activities**.[7] Currently, this is particularly the case in the aerial and maritime domains, and in future it may be likely for ground systems as well.[8] For example, non-state actors, such as terrorist groups, have used UASs to conduct surveillance and have weaponised systems to conduct strikes. In the maritime domain, UMSs can be used 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]

Uncrewed systems are also at risk of being **increasingly weaponised for lethal use**. This can include adapting commercially available unarmed systems.[10] Systems which to-date have primarily undertaken or are intended for non-lethal activities, can also be armed.[11] Indeed, the weaponization of unarmed systems is not restricted to non-state actors; state actors can also purchase and modify unarmed systems. Additionally, in certain instances, these systems do not need to contain a lethal payload to act as a weapon, as the vehicle itself can be used to crash into a target.[12] Beyond lethal attacks, these initially non-offensive systems or components can target civilian or dual-use infrastructure.[13]

As a result, uncrewed systems could **lower 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. Indeed, the ability of uncrewed systems to remove personnel from risk has led to claims that this could incentivise armed hostilities or conflict.[14] Related to this are the challenges that the use of uncrewed systems for lethal purposes can pose **to the interpretation and application of international humanitarian law and international human rights law**, particularly if used without proper constraints or outside a conflict.[15]

Challenges related to the misuse of uncrewed systems can also differ by type of system. For example, there are humanitarian concerns regarding the use of UASs in situations of conflict due to the remote nature of their use, and around how legal responsibility can be enabled and moral obligations duly recorded.[16] Regarding UMSs, while their use is governed by the 1982 United Nations Convention on the Law of the Sea (UNCLOS), there is ongoing uncertainty around the legality of the use of such systems for military activities, particularly in the exclusive economic zone of a coastal state.[17] This is particularly the case for dual-use systems whose ultimate purpose can remain unclear.[18] In the case of UGSs, the use by law enforcement agencies of ground-based robotic systems that can deliver coercive or lethal force could be seen as another trend pointing to the militarisation of such agencies.[19] It also raises legal and regulatory questions around whether and how to enable and approve of the use of lethal force by a UGS.

EXPLOITATION OF SYSTEM VULNERABILITIES

Uncrewed systems can be **vulnerable to interference**, such as by jamming, spoofing, hacking or otherwise disrupting the data links between remotely piloted vehicles and their operators. Such actions, combined with a lack of cybersecurity protection, could lead to data being obtained by other parties, poisoned or deleted.[20] The spoofing of the system's perception ability, such as by tricking the vehicle's sensors into detecting fake obstacles or by manipulating its image-recognition component, could interfere with the system's ability to

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[6] Interviews with anonymous interviewees C (02/12/2021), D (15/12/2021), E (11/11/2021), K (01/02/2022) and L (03/02/2022), and with Luis Merino (27/01/2022) and Geert de Cubber (27/10/2021); Omitola et al. (2018).

[7] Berie & Burud (2018).

[8] Rossiter (2020); Izadi Moud et al. (2018); Balestrieri et al. (2021); Martinic (2014).

[9] Chadwick (2020); Dinstein & Dahl (2020).

[10] Interviews with anonymous interviewees I and J (01/02/2022); Office for Disarmament Affairs (2015).

[11] Interview with Luis Merino (27/01/2022); Scharre (2014); Martinic (2014).

[12] Yaacoub et al. (2021).

[13] Schmitt & Goddard (2016).

[14] Office for Disarmament Affairs (2015); Woodhams & Borrie (2018).

[15] Dorsey & Amaral (2021); Office for Disarmament Affairs (2015).

[16] Interview with Chief Engineer, Trusted Autonomous Systems (21/12/2021); Krähenmann & Dvaladze (2020).

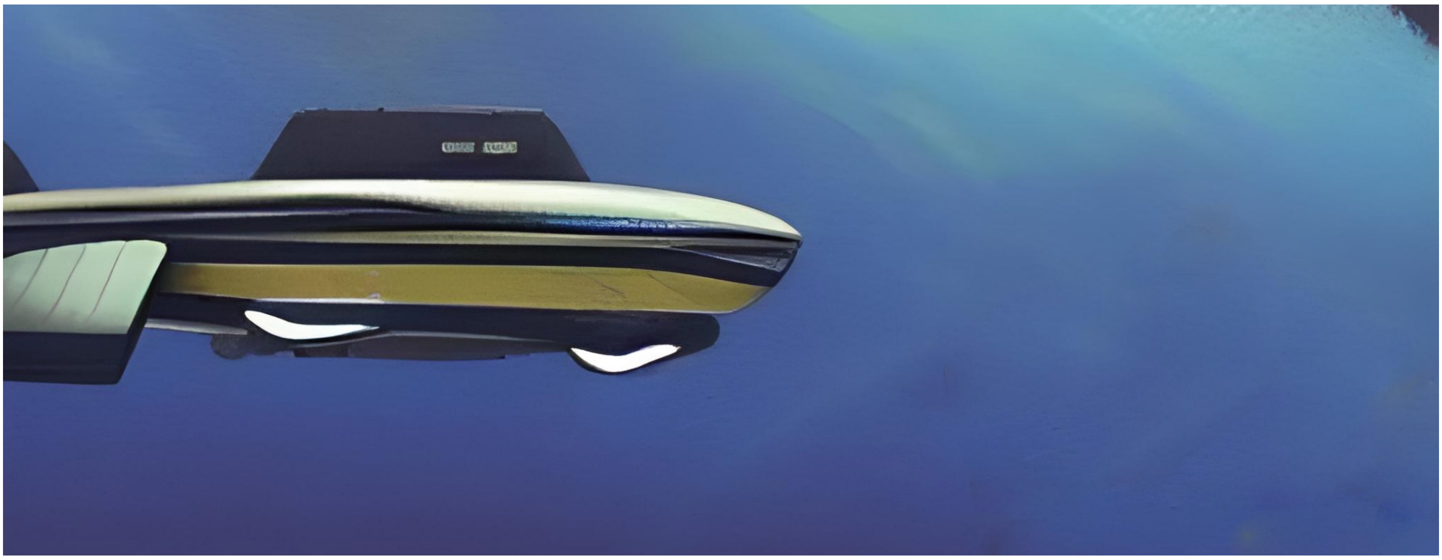
[17] McKenzie (2021).

[18] Chang et al. (2020).

[19] Joh (2016); Sullivan et al. (2016).

[20] Interview with Mostafa Hassanalian (05/11/2021); Silverajan et al. (2018).

[21] See for example Petit et al. (2015).



navigate safely.[21] In a civilian context, such vulnerabilities could potentially be exploited to take control of an uncrewed vehicle as a way to cause harm, particularly against vulnerable targets.[22]

Additionally, there is an **increasing use of open-source technology solutions**, in a move away from private intellectual property. Yet, open access to technology means that there is no control over who obtains access to or knowledge of sophisticated capabilities. Equally, the operator of an uncrewed system that relies on open-source technology may have limited knowledge of who is behind the technology, opening the potential for system vulnerabilities.[23]

SYSTEM-SPECIFIC CHALLENGES

SEPARATION BETWEEN MILITARY AND CIVILIAN UASs BECOMING INCREASINGLY BLURRED

Technological advances are increasingly blurring the lines between military and civilian technologies. This trend is particularly apparent regarding UASs, which are used most in both the military and civilian sectors. Technological advances in civilian UASs have enabled these systems to become increasingly capable of performing complex tasks that would previously have only been possible using military technology. Thus, from a regulatory point of view, export control regimes are struggling to keep pace with rapidly evolving and increasingly capable civilian systems. This has led to certain civilian UASs being classified as dual-use items and therefore being subject to export controls.[24] Consequently, distinguishing military and civilian systems from a technical perspective may no longer be the most relevant approach; instead, differentiation should focus on capability.

ABILITY TO IDENTIFY UMSs

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 facts that it can be difficult to differentiate between crewed and uncrewed systems once in operation, impacting the type of response to such a threat, and that **it can be challenging to assess which systems pose a military threat and which do not.**[25] Threats from UMSs may, for example, take the form of offensive backdoor cyber activities, destruction of underwater infrastructure (including, but not limited to, communications 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 their stealth, such as through designs conceived to mimic aquatic creatures and the use of materials that reduce a system's electromagnetic signatures.[26]

Despite the challenges shared by uncrewed systems across the three domains and the fact that all systems can affect international security, the scope and scale of the threats differ depending on the system. UASs currently cause the greatest challenges to international security because of their widespread use in both the civilian and military sectors and the accessibility of the aerial domain to a range of actors. Moreover, UMSs are becoming an increasing source of challenges to international security. They are not necessarily currently accessible to a large number of actors, and nor are they available in large numbers. However, the development and use of UMSs is increasing. The maritime domain facilitates the use of uncrewed systems given that it is regarded as relatively "uncluttered" and "uncomplicated".[27] Compared to UASs and UMSs, UGSs pose fewer threats to international security given that they are less developed and, thus, their use has been limited to specific areas or for specific activities.

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[22] Yaacoub et al. (2021).

[23] Interview with Chief Engineer, Trusted Autonomous Systems (21/12/2021).

[24] Office for Disarmament Affairs (2015); Sayler (2015); Haider (2020).

[25] Matos et al. (2017).

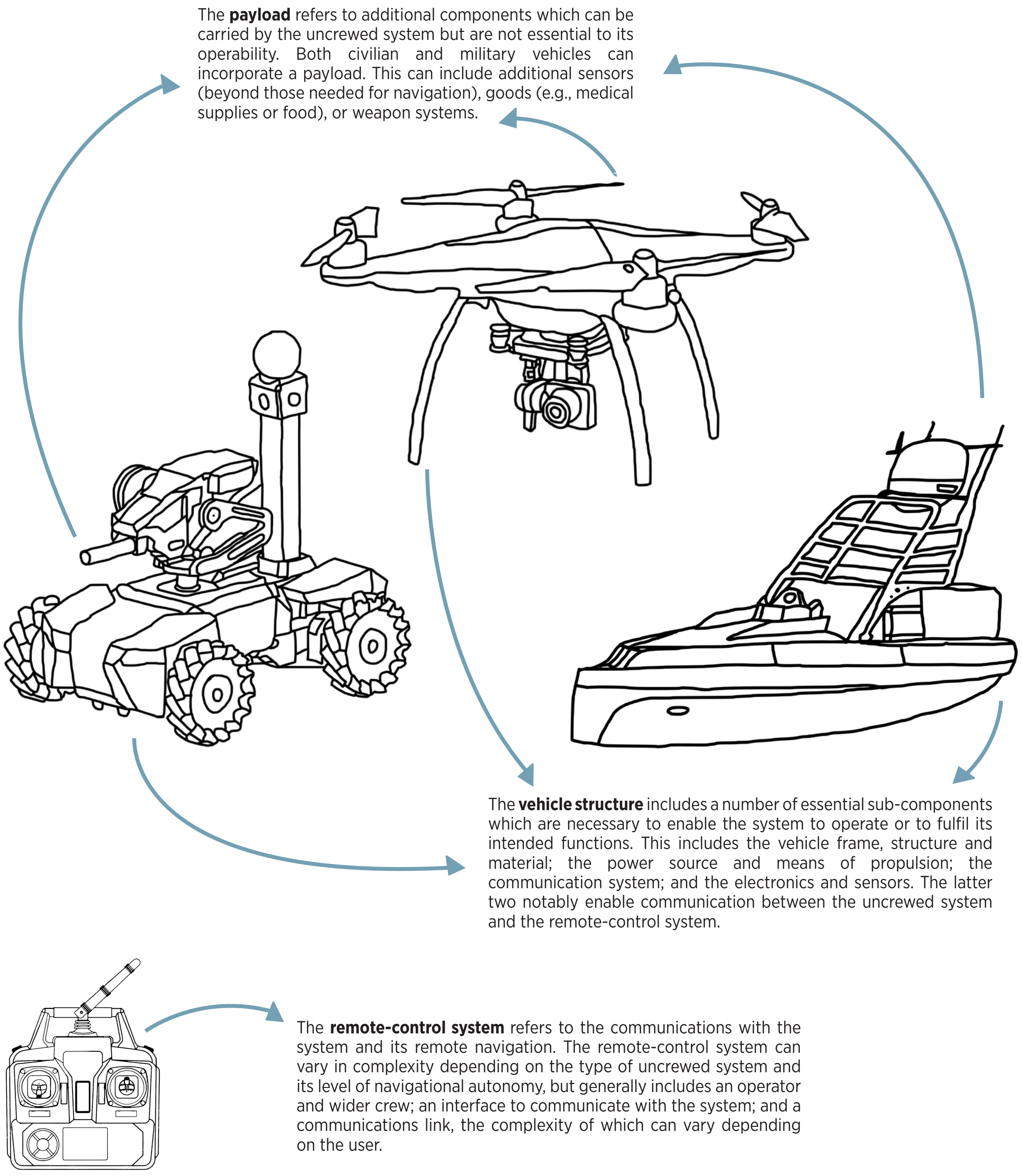
[26] Heintschel von Heinegg (2018).

[27] UNIDIR (2015).

5. KEY COMPONENTS OF UNCREWED SYSTEMS

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

Figure 2: *Key components of uncrewed systems*



The **payload** refers to additional components which can be carried by the uncrewed system 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 **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 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 notably enable communication between the uncrewed system and the remote-control system.

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 uncrewed system 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.

6. AREAS OF INNOVATION

Each type of uncrewed system is faced with technical challenges, some of which are general to all systems and some of which are specific to the domain of operation or the complexity of the system. The main technical challenges facing each system are outlined in table 2.

Table 2: Technical challenges faced by UASs, UGSs and UMSs

UAS	UGS	UMS
• Endurance, particularly for rotary-wing systems • Payload capacity, particularly for rotary-wing systems Propulsion	• Navigation • Environmental challenges (e.g., dirt, mud, dust or rain[28]) • Energy-intensiveness and technically complexity[29]	• Real-time communication, particularly for underwater systems • Long-term power supply • Reliable autonomy for long-term missions

These technical challenges are the focus of ongoing research and innovation seeking to create even more capable systems. The innovations presented in this section are divided by specific components comprising uncrewed systems: vehicle shape, structure, and material; power source and means of propulsion; communications systems; and electronics and sensors. These innovations include both domain-specific developments alongside developments of relevance for all or several domains as well as where developments in one domain are likely to be taken up in another. Each of the following sub-sections provides an introduction to the area of innovation, as well as the implications of relevant innovations, such as for the capabilities of the systems themselves, for arms control instruments and processes, and for international peace and security more generally. The innovations are presented in five tables, each highlighting the domain or domains in which the area of innovation will apply. 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. Box 2 describes other broader areas of technological progress that have an impact on uncrewed systems.

Box 2: Additional areas of innovation

Electronics and components of all types are **becoming increasingly miniaturized**, simultaneously becoming more powerful and, in some cases, cheaper[30] 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 miniaturization could lead to UASs as small as 0.25 centimetres or even 1 millimetre ("smart dust").[31] 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 categorizations.

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.[32] Quantum sensors would, for example, remove the need to rely on GNSS for navigation.[33]

VEHICLE SHAPE, STRUCTURE AND MATERIAL

The vehicle frame – including its shape, structure and material – encompasses the "skeleton" of the uncrewed system, meaning the hardware comprising the body of the vehicle. Of particular importance here is the categorizations of uncrewed systems according to their domain (i.e., aerial, ground or maritime) or, in the case of UASs, wing type, as is the case within current arms control instruments and confidence-building measures and processes. These may become outdated in the future as a result of innovations regarding cross-domain capabilities.

The main areas of innovation are outlined in table 3.

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[28] Rossiter (2020); Balestrieri et al. (2021); Odedra et al. (2009); Interview with Nick Reynolds (12/11/2021).

[29] National Research Council (2005); Balestrieri et al. (2021).

[30] Interviews with Geert de Cubber (27/10/2021), Chief Engineer, Trusted Autonomous Systems (21/12/2021); anonymous interviewee D (15/12/2021).

[31] Hassanalian & Abdelkefi (2017).

[32] Interviews with anonymous interviewees I and J (01/02/2021).

[33] Tucker (2021); Interview with Chief Engineer, Trusted Autonomous Systems (21/12/2021).

Table 3: Areas of innovation related to vehicle shape, structure and material

Area of innovation	Description	Implications	Type of system
Cross-domain systems	There are developments to enable a single uncrewed system to operate across multiple domains.[34] This means that systems are being tested and designed to operate across, for example, the ground and aerial domains, or the maritime and ground domains.	• Potential future discrepancies in terms of the way in which crewed and uncrewed systems are categorized by domain rather than by capability within arms control processes, which could possibly result in a loss of relevance and purpose of such processes	UAS UGS UMS
Advanced materials	Research is progressing to develop advanced materials (including polymers and intelligent, nano, multifunctional and composite materials) for the structure or frame, or to coat the structure of an uncrewed vehicle, the aim being to make structures lighter yet sturdier and more resistant. Advanced materials could also integrate self-healing properties, mimicking biological organisms, with research ongoing to develop these.[35]	• Sturdier and more enduring systems, with increased resistance to shocks (e.g., the impact of bullets) and heat, improved waterproof capacity and hydrodynamics, or even the ability to absorb electromagnetic waves (e.g., to reduce discovery by radar), without increasing weight[36] • Increased attractiveness of systems potentially leading to greater as well as longer-term use	UAS UGS UMS
Wing types	Wing types beyond the traditional fixed and rotary wings may increase, particularly in smaller and less complex UASs. This includes UASs using flapping wings or combining different wing types (e.g., rotors- and fixed wings) in one system. Biomimicry, where synthetic products or systems are modelled on biological systems, has been applied to existing wings so that they resemble wing structures found in nature.	• Ability to overcome the respective limitations of each individual wing type[37] • Overall, increased attractiveness of systems potentially leading to greater use	UAS
Morphing and other capabilities	Research is taking place around the ability of a UAS to change and adapt its wing shape or structure during flight, such as by compressing its rotors or folding its wings (i.e., an expanded scope of movement beyond variable-geometry wings, which are fixed wings which have limited movement). Another area of research seeks to improve and widen the surface types that a UAS can perch or rest on.[38]	• Increased ability of a smaller UAS to enter and navigate narrow areas, such as inside buildings, to manoeuvre around obstacles[39] • Enabling UASs to conduct long-term surveillance while reducing or even stopping power consumption • Overall, increased attractiveness of systems potentially leading to greater use	UAS
Range of locomotion types	Legged systems of various types (e.g., bipedal and quadrupedal) are likely to become more common since they are better suited to challenging terrain. These systems are being joined by other less common types of locomotion that mimic animals or insects, such as snake-like UGSs, which would be better able to navigate difficult terrain and operate in space-constrained environments.[40]	• New and different forms of locomotion could overcome existing challenges with regards to terrain and other obstacles such as space constraints • Security challenges regarding their ability to carry a lethal payload (albeit limited for now)[41]	UGS
Vehicle structure	There are both recent and emerging innovations in the structural shapes of both surface and underwater UMSs in order to allow them to be stealthier and to avoid detection (both hydro- and electro-acoustic as well as visual).[42] 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.[43]	• Harder to detect, making it harder to assess, prevent or mitigate a threat	UMS

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[34] For example: Irving (2021).

[35] For example: Tan et al. (2020).

[36] Trafton (2022); Tomków et al. (2020); Gerigk & Wójtowicz (2015). See also Ferreira et al. (2016) and Zeng et al. (2022).

[37] Such limitations for example include limited endurance for rotary-wing systems, while fixed-wing systems require more space and sometimes a runway for their take-off and landing. For example, biomimetic wings help improve flight capabilities, or reduce detectability and the noise of the systems. Interviews with anonymous interviewees C (02/12/2021) and K (01/02/2022) and David Scaramuzza (22/10/2021); Noda et al. (2018).

[38] Hang et al. (2019).

[39] Interview with David Scaramuzza (22/10/2021); Falanga et al. (2019); Di Luca et al. (2017).

[40] Evans (2013).

[41] Interview with anonymous interviewee D (15/12/2021).

[42] Gerigk (2016).

[43] Olsen et al. (2020).

POWER SOURCE AND MEANS OF PROPULSION

An uncrewed vehicle can be powered by fuel or renewable energy. Innovations in power source and means of propulsion will improve endurance for longer operation times, which is likely to make the use of uncrewed systems more appealing in military operations. Equally, this could improve the capabilities of civilian systems, which currently tend to have a shorter endurance than military systems. This in turn could increase the attractiveness of civilian systems for use by entities with illicit or harmful intent.

The main areas of innovation are outlined in table 4.

Table 4: Areas of innovation related to power source and means of propulsion

Area of innovation	Description	Implications	Type of system
Batteries	One of the limitations of battery-powered uncrewed systems is their endurance. Lithium batteries are the most commonly used today. Research is ongoing to increase their energy density or use new materials (e.g., sulphur) for longer life.[44] Alternative battery types, such as solid-state batteries, would enable greater energy and endurance compared to their lithium counterparts, but costs are currently higher. There is also research regarding the specific use of batteries in a maritime environment, with a focus on improving waterproof batteries.[45]	• Increased endurance of uncrewed systems as well as their electronics • Longer operational durations could be appealing for both legal as well as illegal and harmful activities	UAS UGS UMS
Other types of power source and propulsion method	Other types of power source include solar power (particularly for UASs and UMSs), internal combustion engines (UASs, UMSs and UGSs), and jet fuel or propane (particularly for UGSs). Efforts are underway to improve various power sources and propulsion methods. Additionally, research is ongoing to reduce thermal and acoustic signatures and to increase the reliability and improve the power and energy management of such methods, while also reducing the costs. For example, solar cell technology has been constantly improved in terms of its ability to capture energy while remaining lightweight. Additional innovations, such as the ability to capture infrared light at night, are also being explored.[46] Hybridization is another area seeking to leverage the advantages of combining propulsion methods, for example by combining high energy density solutions (such as fuel cells) with high power density solutions (such as batteries or supercapacitors).[47] There is also innovation specific to certain domains; for example, in the maritime space, there is research to leverage the mechanical energy of marine currents or streams and waves, with the latest innovations demonstrating increasingly high energy yields.[48]	• Longer operational durations could be appealing for legal as well as illegal and harmful activities • Stealthier systems are harder to detect, making it harder to assess, prevent or mitigate a threat	UAS UGS UMS
Hydrogen fuel cells	This comprises compressed hydrogen gas and liquid hydrogen fuel cells. The technology behind compressed hydrogen is more mature than that of liquid hydrogen, although there are efforts to make both viable solutions. The use of compressed hydrogen gas and liquid hydrogen fuel cells would increase stealth.[49] It would also enable higher-altitude and quieter flights for UASs, as well as longer-range missions for both UASs and UMSs.	• Longer operational durations could be appealing for legal as well as illegal and harmful activities • Stealthier systems are harder to detect, making it harder to assess, prevent or mitigate a threat	UAS UMS

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[44] See for example a new breakthrough in lithium-sulphur batteries: Drexel University (2022).

[45] Budiyono (2009).

[46] See for example: Deppe & Munday (2019).

[47] Shah & Czarkowsi (2018).

[48] Clemente et al. (2021).

[49] Boukoberine et al. (2019).

COMMUNICATIONS SYSTEM

The communications system encompasses all relevant elements that link the uncrewed vehicle and its operator. Uncrewed systems use antennas to transmit and receive data, or even act as a communications relay. Antennas are thus critical for uncrewed systems, particularly for those that do not integrate autonomous navigation features. Innovations are strengthening the link between the vehicle and the remote-control system, which helps to ensure better data connectivity and allow longer distances between the vehicle and the operator. As such, this can improve the use of a vehicle more generally, as well as its ability to share data collected while in use.

The main areas of innovation are outlined in table 5

Table 5: Areas of innovation related to the communications system

Area of innovation	Description	Implications	Type of system
Antennas	Novel antenna designs and ongoing innovations around different antenna types (e.g., to increase signal strength) are being integrated into uncrewed systems.	• Better control over greater distances by the operator • Increased value of using uncrewed systems to carry out a range of long-distance tasks	UAS UGS UMS
Radiofrequency communications technology	Notable innovations regarding cellular connectivity and transmission of data include the roll-out of fifth-generation (5G) cellular networks and, in future, other even faster generations of cellular technologies. Another area of research is the adaption of software-defined cognitive radios. These radios aim to use the available radiofrequency (RF) spectrum more effectively to overcome the competition in certain RFs due to their use by an increasing number of electronic devices, and to increase the overall resilience of RF communications. As such, cognitive radios aim to select the most appropriate channel "smartly" by sensing and adapting to the radio spectrum environment rather than by using the frequency specifically defined in the hardware.[50]	• Higher rates of data transfer by civilian UASs • UASs equipped with cognitive radios would be more resistant to counter-UAS solutions using RF jamming[51] • Due to the technical constraints of the maritime environment, innovations in cellular data transmission and connectivity would allow for potentially higher rates of data transfer for UMSs, even potentially in the underwater environment	UAS UMS
Satellite communications	Innovations in satellite communications (SATCOM) include reductions in the size and weight of the hardware, enabling it to fit onto smaller systems. Other innovations in this field seek to continue to improve the accuracy and speed of signals.[52] Use of SATCOM can also be combined with the use of cellular networks, such as 5G, to enable more rapid communication. 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.	• Navigation beyond visual line of sight (i.e., when the operator can no longer see the vehicle without technological support) and to transmit data • Improved oversight over surface UMSs, enabling longer missions	UAS UMS
Optical communications	Developments in this area include the use of optical wireless communications as an alternative to RF communications technology. This could potentially form the basis of 6G, enabling even faster data transmission through increased bandwidths while not being prone to RF interference (e.g., signal jamming).	• Navigation beyond the visual line of sight • Faster or more accurate decisions and outcomes based on communicated data	UAS UGS
Hydro-acoustic communications	In recent years, there have been advances and innovations in the field of hydro-acoustic communications, 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.[53]	• Navigation beyond the visual line of sight • Faster or more accurate decisions and outcomes based on communicated data	UMS

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[50] Santana et al. (2021).

[51] Santana et al. (2021).

[52] Zolich et al. (2019).

[53] Kozhemyakin et al. (2018).

ELECTRONICS AND SENSORS

The electronic elements and sensors embedded in an uncrewed system enable it to perform key functions such as navigation and decision-making. Sensors notably capture data about their surroundings and thus play a critical role in navigation and decision-making by a system, such as by detecting objects to avoid collisions. A range of sensors, including cameras and radars, along with AI and computing power aid navigation. They are key in areas with no global navigation satellite system (GNSS) signal or to reduce the dependence of the system on GNSS.[54]

Of particular importance here is research seeking to ensure that uncrewed systems can increasingly navigate autonomously. A reduction, or even a removal, of human control for longer periods of autonomous operation has implications for how these systems are used as well as the ability to have oversight into their decisions and actions. This becomes even more critical when such systems, particularly UASs and UGSs, operate in complex or congested environments, such as a battlefield or urban settings. In such situations, the potential for error and unintended consequences is higher than in uncongested environments. Overall, advances in electronics and sensors – whether these improve guidance, navigation and control or sensing, perception and autonomy – increase the attractiveness of using uncrewed systems due to these being better able to navigate in different environments and being less reliant on the operator.

In the case of electronics and sensors for guidance, navigation and control, the main areas of innovation are outlined in table 6. In the case of electronics and sensors for sensing, perception and autonomy, the main areas of innovation are outlined in table 7.

Table 6: Areas of innovation related to guidance, navigation and control

Area of innovation	Description	Implications	Type of system
Sensors for navigation	There are constant developments to sensors in order to improve their performance, notably to ensure redundancy and higher resolution data collection, while also reducing their costs.[55] For example, optical sensors combined with AI algorithms can aid navigation without reliance on GNSS. This type of technique is expected to continue improving and to make increasing use of AI and sensor improvements.	• Improved navigation of systems • Enabling the use of autonomous navigation • Facilitating the use of uncrewed systems in contested or GNSS-denied environments by removing reliance on GNSS	UAS UGS UMS
Global navigation satellite system	Technological advances in this area include the ability to pick up and exploit extremely low-level GNSS signals, as well as the improvement of navigation using this technology. These advances will also be enabled through the expected increase in the number of satellites.	• Improved accuracy of positioning of uncrewed vehicles and thus the precision of their navigation[56]	UAS UGS UMS
Inertial navigation system	An inertial navigation system (INS), which includes an inertial measurement unit measuring the speed, rotation and position of a vehicle and a computational unit, is a core aspect enabling navigation, as it does not rely on an external element, such as satellite data.[57] Research is seeking ways to miniaturize INSs without reducing their performance or accuracy.[58] Furthermore, the accuracy of an INS can also be complemented by the use of high-precision cameras.[59]	• Improved autonomy of smaller UASs no longer restricted only to larger models • Improved autonomy of UMSs, particularly for systems which have limited or no ability to rely on satellite data	UAS UMS
Hydro-acoustic navigation	Several innovations seek to enable a wider range of hydro-acoustic navigation systems as well as 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.[60] Additionally, the transmission and reception of electro- or hydro-acoustic waves provides a UMS with a modelled map of its environment and surroundings and thus enables it to navigate. This is particularly important for underwater UMSs, but also has applicability to surface UMSs.	• Improved navigation of both underwater and surface UMSs	UMS

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[54] Interview with anonymous interviewee E (11/11/2021).

[55] Interviews with anonymous interviewees E (11/11/2021) and K (01/02/2022), and with David Hambling (08/12/2021), Bruno Martens (02/12/2021), Geert de Cubber (27/10/2021), Luis Merino (27/01/2022), and David Scaramuzza (22/10/2021).

[56] Interview with Geert de Cubber (27/10/2021); Yong Ko et al. (2016).

[57] Bao et al. (2020).

[58] See for example Honeywell (2021).

[59] Sahoo et al. (2019).

[60] Jones et al. (2013).

Table 7: Areas of innovation related to sensing, perception and autonomy

Area of innovation	Description	Implications	Type of system
Sensors	Advances in sensors (see table 6) 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 an uncrewed system to perceive and therefore respond to its environment with limited operator input.	• Better data collection as well as potential autonomy	UAS UGS UMS
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), enhancing perception/surveillance (e.g., object detection, classification and tracking), planning and action. Advances continue, aided by the growth in computing power as well as the amount of data available to train on.	• Enhanced ability of uncrewed systems to autonomously navigate, including without the need to rely on GNSS[61] • More intelligent operations within their environment and with regard to other systems • Overall reduction of human involvement during a mission	UAS UGS UMS
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. For example, AI can be embedded into specifically created chips. Other emerging approaches include neuromorphic computing and their related chips, which mimic the human brain, and the use of materials other than silicon (e.g., carbon nanotubes).[62] In future, more innovations are to be expected, such as integrating computing and storage capabilities, to further reduce power consumption.[63]	• Improved level and speed of operations, particularly those relying on AI • Reduced reliance on the operator and remote-control station to process data captured by a system	UAS UGS UMS
Robotic teaming	Robotic teaming, or collaboration to complete a task, including between systems across different domains, will continue to improve.[64] This includes swarming-type technology, where a number of systems are deployed at once. True "swarming"[65] remains further in the future.	• Enhanced threat to security • Harder to effectively counter malicious systems operating in this fashion	UAS UGS

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[61] Amer at al. (2019); Interview with David Scaramuzza (27/10/2021).

[62] Interviews with Geert de Cubber (27/10/2021), Luis Merino (27/01/2021); Chief Engineer, Trusted Autonomous Systems (21/12/2021); Dilmegani (2022); Wellers & Fitter (n.d.).

[63] Li et al. (2019).

[64] Interview with Chief Engineer, Trusted Autonomous Systems (21/12/2021).

[65] There is no agreed definition for the term "swarming". From a technical point of view, however, and for the purpose of this publication, swarming is defined as a group of either homogenous or heterogenous uncrewed systems operating as a networked entity and taking collective decisions through the use of AI, without the use of a central coordinator. Most instances of so-called swarms have tended to be pre-programmed or have some form of remote control, therefore not adhering to this definition of "true swarming", although developments in this regard should be noted and followed closely (see, e.g., Zhou et al. 2022). Due to the lack of knowledge of the algorithms enabling behaviour of increasingly AI-enabled uncrewed systems, it can however be challenging to distinguish the differences between instances of robotic teaming versus true swarming. Regardless, the use of a group of uncrewed systems working jointly remains a serious security challenge, which further increases with the addition of increased autonomy. See also Ekelhof & Persi Paoli (2020); Verbruggen (2019); Brambilla et al. (2013).

7. CONCLUDING REMARKS

Uncrewed systems across the three domains of operation – in the air, on land and at sea – have all been used and developed for both military and civilian settings, although to different extents. **UASs have been the most used to-date** due to the wide range of areas in which they can be applied, in both military and civilian sectors, as well as the comparatively fewer technical challenges impeding their wider use and application. And while most challenges posed by the systems to international security are the same across the domains, the scale and scope differs greatly, notably due to this difference in use. Indeed, UASs currently present the greatest risk to international security, while concerns regarding UMSs are growing due to their increased potential for development and use by militaries.

While UMSs and UGSs have not yet seen widespread use to the same extent, **all types of uncrewed system are attractive due to the wide-ranging areas of application.** In the military sector, uncrewed systems can be used for force projection, to deliver results at a distance at a lower cost than when using crewed systems. In particular, **UMSs have gained traction and their use is increasing** in both military and civilian settings. UGSs also benefit from many technological advances deriving from the civilian sector, notably through the employment of robots in industrial settings and the ongoing developments in the field of autonomous cars. However, ground-based systems continue to face significant technical challenges – notably due to operating in a more challenging environment – which impede their greater use compared to UASs and UMSs.

Technological innovation is also a source of current and future challenges. Some of these challenges have an impact on the effectiveness and attractiveness of the systems, in addition to affecting their categorisation in export control regimes and confidence-building mechanisms. Furthermore, technological progress is occurring in many areas of the enabling technology that is common to all systems. These notably include advanced materials, power sources and propulsion, sensors, artificial intelligence, and computing power. As such, **advances currently applicable to one type of system may be transferable and likely to occur in other types of systems too**, albeit with differences between how these may be integrated within civilian or military models – and thus how and whether it may have an impact on the rise of dual-use items.

Moreover, **technological progress driving the capabilities of uncrewed systems is not only in the purview of states**. A lot of innovation is driven by the private sector. At the same time, the number of suppliers of uncrewed systems has also increased, which can make controlling and regulating the supply side more complex. This has also widened the access of technologically advanced systems to a broader spectrum of actors, with this democratisation of access – and supply – having an impact on the risk that these systems pose to international security.

Now and in the future, such advances may have a multitude of impacts. **Conventional arms control processes, such as confidence-building mechanisms and export control regimes, may no longer achieve their goals** if they cannot accurately reflect evolution in the development and use of uncrewed systems. As a result, they may lose relevance. **Changes may also be seen in the way in which such systems are used and for what purposes, as well as how armed conflict is waged.** This could be driven by a number of factors. On the one hand is the increased accessibility of more affordable uncrewed systems – compared to their crewed equivalents – or the increased use of smaller, commercial models in addition to larger, more traditional military models. On the other hand, we may also witness a compounded effect of a range of the technological innovations outlined in this paper, whereby smaller, more efficient, longer-lasting systems can function more stealthily, more autonomously and even jointly within and across domains. As such, it is not only important but necessary to actively monitor and take adequate action at the multilateral level, involving all relevant communities of interest, to manage and mitigate the threats and challenges posed by uncrewed systems to international peace and security.

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
Mostafa Hassanalian	New Mexico Institute of Mining and Technology	5 November 2021
Interviewee E	–	11 November 2021
Nick Reynolds	Royal United Services Institute (RUSI)	12 November 2021
Bruno Martens	UNICRI	2 December 2021
Interviewee C	-	2 December 2021
David Hambling	Science and technology journalist	8 December 2021
Interviewee D	-	15 December 2021
Chief Engineer	Trusted Autonomous Systems	21 January 2022
Luis Merino	Universidad Pablo de Olavide	27 January 2022
Interviewee I	–	1 February 2022
Interviewee J	–	1 February 2022
Interviewee K	–	1 February 2022
Interviewee L	-	3 February 2022

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