UNCREWED AERIAL SYSTEMS: A PRIMER

SARAH GRAND-CLÉMENT & THEÒ BAJON

SUMMARY OF KEY POINTS

- Uncrewed aerial systems (UASs) are not homogenous; different types of system vary in their size, weight, endurance, wing type and other such characteristics. While military UASs tend to have a higher endurance and are larger than civilian UASs, advances in the latter mean that the distinction between high-end civilian systems and lower-end military systems is increasingly blurred.
- UASs currently cause a greater challenge to international security than uncrewed maritime and ground systems. This is due to the maturity of the aerial systems, the growth in their use and the accessibility of the aerial domain to a range of actors. Notable challenges posed by UASs relate to their ease of proliferation and misuse, the potential for military UASs to lower the threshold for the use of force, and the ethical and legal challenges surrounding the use of lethal uncrewed systems.
- Despite their capabilities, UASs nonetheless face certain technical challenges that can limit their use or performance. Research and innovation are seeking to address challenges related to power sources and means of propulsion in order to improve the endurance of UASs and their ability to carry greater payloads. Developments in the fields of sensors, artificial intelligence and computing power are also needed to increase navigational autonomy and reduce reliance on the operator or satellite data.

INTRODUCTION

The production and use of uncrewed aerial systems (UASs) – which include vehicles that can be piloted either remotely or semi-autonomously – have increased. The term UAS encompasses both the vehicle (the uncrewed aerial vehicle, UAV) 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 UAS technological developments and their security implications. Similar primers are also available on uncrewed ground systems (UGSs) and uncrewed maritime systems (UMSs), 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 UAS, 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 UASs, 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.

UNIDIR UNITED NATIONS INSTITUTE FOR DISARMAMENT RESEARCH

DIFFERENT TYPES OF UAS

There is no universal classification of UASs. UASs, whether military or civilian, can be differentiated according to technical characteristics such as maximum altitude, maximum weight at take-off, endurance and range, payload, size, speed, and weight; and, for military systems, whether they are armed or not.[1] When comparing military and civilian UASs, the former will tend to have a higher endurance and payload capacity, as well as a higher cost.[2]

Another characteristic that can be used to differentiate UASs is by wing type. This is currently how UASs are distinguished within the categories of UNROCA.[3] Broadly, UASs can have one of three different wing types:

- **Rotary-wing:** These systems can have one, four, six or more rotors. Rotary-wing UASs are employed by many types of actors. While they are primarily used by civilian hobbyists and the private sector for commercial purposes, they are also employed by state and non-state armed groups. 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:** These systems are used by military and civilian actors (e.g., for commercial purposes such as agriculture, or peacekeeping). 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 domains.

While there are different types of UAS, 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., both crewed and uncrewed vehicles can have rotors or fixed wings) 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 that crewed aerial vehicles have a pilot on board, unlike UAVs, which have no one on board. Other differences arise from this distinction, as outlined below. While the 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 a UAS can be operated and what inputs are needed from the UAS operator vary depending on the type of system, its complexity, and whether it is a military or civilian system. In a remotely controlled UAS, 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 an aerial platform has someone onboard. Some are physical: for example, without a pilot inside an aircraft, 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 the life of the UAV operator is lowered or even removed compared to that of an aircraft pilot if an aircraft is attacked. Another difference relates to the fact that, without a pilot, a UAV is reliant on sensors and on communication networks for contact with its operator. These electronic elements all operate within the electromagnetic spectrum. As such, UASs are more susceptible to jamming (i.e., interference with its electronics via the electromagnetic spectrum) as there is no pilot onboard to take manual control of the system. In response, there is ongoing research seeking to improve the resilience of UASs, as described in the section below on areas of innovation.

1 Hassanalian & Abdelkefi (2017); Dorsey & Amaral (2021); Giordan et al. (2020). On the military classification, states and entities classify UAS according to various different categories. 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, NATO divides UASs into three classes, based on weight.

2 Zwijnenburg & Postma (2018).

3 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.

FUNCTIONS OF A UAS

UASs are being developed and used for military and civilian use. Figure 1 displays the functions of UASs that are solely military and solely civilian, as well as functions shared across both domains.

Given that functions undertaken by military and civilian UASs are largely similar, differences between the systems focus particularly on their technical capabilities.

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

Military functions	Military and civilian functions	Civilian functions
> Target acquisition > Strike operations (if armed)	> Communication and data relay > Logistics (e.g. resupplying, transport and delivery of goods, inventory management) > Monitoring, intelligence, surveillance and reconnaissance > Search and rescue	> Hobbyist (e.g., photography) > Commercial use (e.g., internet provision)

CURRENT CHALLENGES TO INTERNATIONAL SECURITY

Compared to uncrewed maritime and ground systems, UASs currently cause the greatest challenges to international security. This is due to UASs being mature systems, their use being widespread in both the civilian and military domains, and the accessibility of the aerial domain to a range of actors. Some of these challenges are also specific to uncrewed systems due to the unique nature of these systems (as explained in box 1). The following is a non-exhaustive list of challenges to international security posed by UASs:

- **Proliferation and misuse:** UASs, and in particular civilian-grade systems, are accessible to a large number of actors (military and civilian, state and non-state). Several factors facilitate access, notably lower costs than crewed systems, ease of use, the accessibility of the components and, increasingly, the application of advanced technology, although performance levels vary immensely between UASs.[4] The democratisation of access to UASs across a spectrum of actors increases the probability of them being diverted for use in illicit activities.[5] For example, non-state actors, such as terrorist groups, use UASs to conduct surveillance or weaponise systems to conduct strikes. This can include adapting commercially available unarmed systems for lethal use.[6] However, the weaponization of unarmed systems is not restricted to non-state actors; state actors can also purchase and modify unarmed UASs. Additionally, the weaponisation issue is compounded by the fact that a UAS does not need to contain a lethal payload to act as a weapon, as the vehicle itself can be used to crash into a target.[7]
- **Separation between military and civilian systems becoming increasingly blurred:** Technological advances are increasingly blurring the lines between military and civilian technologies, with this trend also apparent regarding UASs. The technological advances of 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 regime thresholds 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 – in other words, items that can have both a military and a civilian application and are therefore subject to export controls.[8] Consequently, distinguishing military and civilian systems from a technical perspective may no longer be the most relevant approach; instead, differentiation should move to focus on capability.
- **Change to the threshold for the use of force:** Military UASs (and other types of uncrewed system) 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. Additionally, their ability to remove personnel from risk has led to claims that this could incentivise armed hostilities or conflict.[9]

4 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 (17/01/2022) and Geert de Cubber (27/10/2021).
5 Berie & Burud (2018).
6 Interviews with anonymous interviewees I and J (01/02/2022); Office for Disarmament Affairs (2015).
7 Yaacoub et al. (2020).
8 Office for Disarmament Affairs (2015); Sayler (2015); Haider (2020b).
9 Office for Disarmament Affairs (2015); Woodhams & Borrie (2018).

- **Ethical and legal challenges:** The use of UASs 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.[10] There are also humanitarian concerns regarding the use of UAS in situations of conflict, in particular due to the remote nature of their use, and also around how legal responsibility can be enabled and moral obligations duly recorded.[11]
- **Exploitation of system vulnerabilities:** UASs are also vulnerable to interference, such as by jamming, spoofing, hacking, or otherwise disrupting the data links between remotely piloted vehicles and their operators. Such actions, which play a role within counter-UAS operations (see box 2), could lead to data being obtained by other parties, poisoned or deleted.[12] Additionally, there is an increasing use of open-source technology solutions, and away from private intellectual property. Yet, open-source access means that there is no control over who obtains access to or knowledge of sophisticated capabilities. Equally, the operator of a UAS that relies on open-source technology may have limited knowledge of who is behind the technology, opening the potential for system vulnerabilities.[13]

In response to these challenges, a range of countermeasures have been and continue to be developed to prevent and mitigate security threats posed by UASs (see box 2).[14]

Box 2: Counter-UAS and counter-counter-UAS technology

As UASs are increasing in number, so are counter-UAS (C-UAS) solutions. To be effective, C-UAS solutions need to be able to detect and intercept UAVs. A UAV can be detected by its visual, thermal or acoustic signatures as well as by its use of the radio frequency (RF) spectrum. Based on a 2019 assessment of C-UAS solutions, the most common detection methods use RF and radar.[15]

Once detected, there are several ways in which a UAS can be countered, including kinetic and non-kinetic force:

- **Kinetic force** can involve using missiles, projectiles or another UAS to cause a collision. Nets can also be used to catch a UAV or entangle its rotors to prevent it from flying.
- **Non-kinetic force** can involve using high-power lasers to destroy the UAV; degrading and damaging its electronic components using high-powered microwaves; dazzling its sensors using a low-powered microwave; jamming RF communications between the system and the operator; or jamming the link between the UAS and its satellite link (global navigation satellite system, GNSS).

Based on a 2019 assessment of C-UAS solutions, the most common interdiction methods are RF and GNSS jamming.[16]

As C-UAS solutions expand, so will counter-C-UAS capabilities, particularly in the military domain. The technological advances described below focus on creating stealthier and less identifiable systems, such as by reducing the size or diminishing the acoustic signature of the UAV. This is also providing an additional impetus to develop systems that can navigate autonomously: these would be less reliant on RF communications and could also navigate with reduced GNSS dependency.

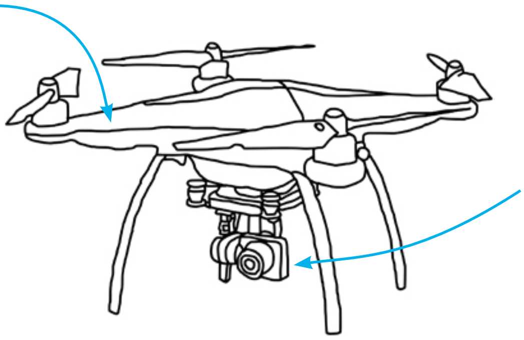
10 Dorsey & Amaral (2021); Office for Disarmament Affairs (2018).
11 Interview with Chief Engineer, Trusted Autonomous Systems (21/12/2021); Krähenmann & Dvaladze (2020).
12 Interview with Mostafa Hassanalian (05/11/2021)
13 Interview with Chief Engineer, Trusted Autonomous Systems (21/12/2021).
14 See for example the *Technical Guidelines to Facilitate the Implementation of Security Council Resolution 2370 (2017) and Related International Standards and Good Practices on Preventing Terrorists from Acquiring Weapons*, which includes measures relating to UASs.
15 Michel (2019).
16 Michel (2019).

KEY COMPONENTS OF A UAS

Most UASs 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.

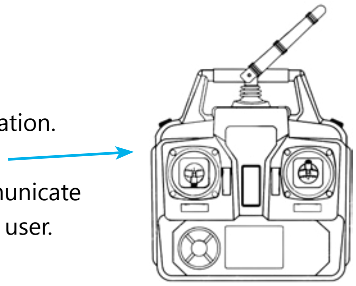
Figure 2: Key components of a UAS

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 UAS and the remote-control system.



The **payload** refers to additional components which can be carried by the UAS 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 weapons 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 UAS 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

While the technical capabilities of UASs have progressed rapidly, these systems continue to face several technical challenges, although these differ depending on the complexity of the systems. These technical challenges are the focus of ongoing research and innovation, which is seeking to create even more capable systems. The main technical challenges currently faced by UASs include endurance, payload capacity and propulsion.

The technological innovations outlined below include developments that are specific to UASs 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.

Vehicle shape, structure and material

The vehicle frame encompasses the "skeleton" of the UAV, meaning the hardware comprising the body of the system. Of particular importance here is the categorisations of systems according to their domain (i.e., air, ground or maritime) or wing type, as is the case within arms control processes. These may become outdated in the light of changes in the way that wing types are conceptualised and as a result of innovations regarding cross-domain capabilities.

The main areas of innovation include:

- **More types of wing:** Different types of wing beyond the traditional fixed and rotary wings may be introduced, particularly in smaller and less complex UAVs. This includes UAVs using flapping wings or combining different wing types in one system (e.g., both rotors and fixed wings), to help overcome the respective limitations of each individual wing type.[17] Such limitations include limited endurance for rotary-wing systems, while fixed-wing systems require more space and sometimes a runway for their take-off and landing. 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. This can help to improve flight capabilities or reduce detectability and the noise of the systems.[18]
- **Cross-domain systems:** There are developments to enable UASs to operate across the land, sea and air domains. For example, there have been demonstrations of aerial systems that are able to operate underwater as well as aerial systems able to operate on land.[19] Advances in this area signal potential future discrepancies in the way in which systems (whether crewed or uncrewed) are categorised by domain rather than by capability within arms control processes.

17 Interviews with anonymous interviewees C (02/12/2021) and K (01/02/2022) and with David Scaramuzza (22/10/2021).
18 Noda et al. (2018).
19 For example, Irving (2021).

- **Advanced materials:** Research is progressing to develop advanced materials for the structure or airframe or to coat the structure of a UAV, which could make the airframe lighter, stronger or more resistant to heat.[20] This aims to improve the endurance of the UAV. Coatings can help increase the protection of the UAV or even absorb electromagnetic waves (e.g., to reduce discovery by radar), without increasing weight.[21] Advanced materials could also integrate self-healing properties, mimicking biological properties, and research is ongoing to develop these for application on UASs. Overall, application of advanced materials to UASs aims to create sturdier and more enduring systems.
- **Morphing and other capabilities:** Research is taking place around the ability of a UAV 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). This area of innovation could increase the ability of a smaller UAV to enter and navigate narrow areas, such as inside buildings, or to manoeuvre around obstacles.[22] Another area of research seeks to improve and widen the surface types that a UAV can perch or rest on, to enable it to conduct long-term surveillance while reducing or even stopping power consumption.[23]

Power source and means of propulsion

A UAV can be powered by, for example, fuel or renewable energy. Of particular importance here is that innovations will enable UASs – and in particular civilian systems, which tend to have a shorter endurance than military systems – to perform for longer, thus potentially increasing their range of action. Improved endurance could make the use of UASs 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 UAVs is their endurance. Lithium batteries are the most commonly used today.[24] Alternative battery types, such as solid-state batteries, would enable greater energy and endurance compared to their lithium counterparts, but costs are higher. Battery advances would enable increased endurance of UASs, and in particular civilian UASs. Improving the endurance of civilian UASs may lead to some systems being classified as dual-use goods, based on existing categorisations. Additionally, higher endurance also presents a security risk due to the ability to use a UAS for longer periods, as it could be vulnerable to attack, but it could equally be seen as an appealing tool for illegal or harmful activities.
- **Hydrogen fuel cells:** Compressed hydrogen gas and liquid hydrogen fuel cells enable longer-range, higher-altitude and quieter flights, as well as a reduced heat signature compared to battery-powered UAVs. As such, the use of hydrogen fuel cells would increase UAS stealth.[25] The technology behind compressed hydrogen remains more mature than that of liquid hydrogen, although there are efforts to make both viable solutions.
- **Other types of power source and propulsion method:** Other types of power source include solar cells and internal combustion engines. Efforts are underway regarding both technologies, such as to improve their abilities and reduce their thermal and acoustic signature. Research on the use of a combination of propulsion methods to improve the power and energy management and system performance of UASs is also ongoing.[26] Similarly, there is also research and innovation on methods for in-field power and energy resupply, such as battery swaps and beamed power, again with the aim of enabling greater endurance and longer flights.

Communication system

The communication system encompasses all relevant elements that link the UAV and its operator. Of importance here is that innovations strengthen the link between the UAV and the remote-control system, also helping to ensure better data connectivity between the vehicle and the ground user.

The main areas of innovation include:

- **Radio frequency communication 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. In particular, 5G will enable higher rates of data transfer by civilian UASs. Another area of research is on adapting software-defined cognitive radios for UASs. These radios aim to use the available 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.[27] UAS equipped with cognitive radios would therefore be more resistant to C-UAS solutions using RF jamming.[28]

20 See for example Ferreira et al. (2016).
21 See for example Zeng et al. (2022).
22 Interview with David Scaramuzza (22/10/2021); Falanga et al. (2019); Di Luca et al. (2017).
23 Hang et al. (2019).
24 See for example a new breakthrough in lithium-sulphur batteries: Drexel University (2022).
25 Boukoberine et al. (2019).
26 Gong et al. (2018).
27 Santana et al. (2021).
28 Santana et al. (2021).

- **Satellite communications:** Satellite communications (SATCOM) are already used in certain instances to enable the use of a UAS beyond visual line of sight (i.e., when the UAS operator can no longer see the UAV without technological support) and to transmit data. SATCOM innovations include reductions in the size and weight of the hardware, enabling it to fit onto smaller UAVs. Use of SATCOM can also be combined with the use of cellular networks, such as 5G, to enable more rapid communication.
- **Optical communications:** Developments in this area include the use of optical wireless communication as an alternative to RF communication 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).
- **Antenna innovations:** UASs use antennas to transmit and receive data, or even act as a communication relay. They are thus critical for UASs, including those that do not integrate autonomous navigation features. Novel antenna designs and ongoing innovations around different antenna types (e.g., to increase signal strength) are being integrated into UASs.

Electronics and sensors

> The electronic elements and sensors embedded in a UAS enable it to perform functions such as navigation and decision-making. Of particular importance here are efforts to ensure that UAVs 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 UAVs to function autonomously in complex environments, such as the battlefield or urban settings.

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

- **Sensor improvements for navigation:** Sensors capture data about their surroundings and thus play a critical role for navigation and decision-making by a system, such as by detecting objects to avoid collisions. A range of sensors, including cameras and radars, aid UAS navigation, along with AI and computing power. There are therefore constant developments to sensors in order to improve their performance while also reducing their costs.[29] Sensors are also key in areas with no GNSS signal or to reduce the dependence of the UAS on GNSS. 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. These developments aim to improve the use of UASs in contested environments.
- **Global navigation satellite system:** Continuous improvement in satellite technology and an expected increase in the number of satellites will improve the accuracy of positioning of UAVs and thus the precision of their navigation and ability to land.[30]
- **Inertial measurement unit:** An inertial measurement unit (IMU) measures the speed, rotation and position of a system, thus aiding with navigation, particularly when GNSS is not available. Research is seeking ways to miniaturise IMUs without reducing their performance or accuracy.[31] These innovations are of particular relevance to smaller UAVs, as this could help improve the autonomy of these systems, and not only larger UAVs.

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

- **Sensor improvements:** Advances in the sensors 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 UAV 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), enhancing perception (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. As AI algorithms improve along with sensor data, this will help improve the ability for UASs to autonomously navigate, including without the need to rely on GNSS.[32]
- **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 and remote-control station to process data captured by a UAV.
- **Robotic teaming:** Robotic teaming, or collaboration to complete a task, including between systems across different domains, will continue to improve.[33] This includes swarming-type technology, where a number of systems are deployed at once, although true swarming still remains further into the future.

29 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) and David Scaramuzza (22/10/2021).
30 Interview with Geert de Cubber (27/10/2021).
31 See for example Honeywell (2021).
32 Amer at al. (2019).
33 Interview with Chief Engineer, Trusted Autonomous Systems (21/12/2021).

Box 3 describes other broader areas of technological progress that have an impact on UASs as well as other types of uncrewed system.

Box 3: Additional areas of innovation

Electronics and components of all types are **becoming increasingly miniaturised**, simultaneously becoming more powerful and, in some cases, cheaper.[34] 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 miniaturisation could lead to UASs as small as 0.25 centimetres or even 1 millimetre ("smart dust").[35] 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.[36] Quantum sensors would, for example, remove the need to rely on GNSS for navigation.[37]

CONCLUDING REMARKS

Uncrewed aerial systems possess a wide range of application areas and, for that reason, there is interest in further developing these systems and improving their capabilities. The areas of research and innovation outlined above will be pursued in both the military and the civilian sectors, although priorities are different across and within these sectors. As such, the types of innovation that will be seen across different types of UAS will be different, as will the timelines for their development and use. For example, the ability to use a UAS in GNSS-denied environments is a much higher priority in the military domain than it is for the civilian sector. Similarly, the civilian sector will place a greater emphasis on developing rotary-wing systems with improved endurance and navigation in order to facilitate commercial ventures.

Increased autonomy and stealth, improved endurance and payload capability, and better sensors to capture more and higher quality data are some of the expected technological improvements to UASs that will have an impact on conventional arms control as well as on international security. Some of this impact is already noticeable and will continue. This includes the challenges for export control based on the technical parameters for UASs, leading to questions as to how to better manage the distinction between military and civilian systems. Other consequences of technological improvements to UASs will be felt in military conflicts, as states seek to distance personnel further from the battlefield and to improve operational success. They will also be felt more widely, as the capabilities will increasingly become available to non-state (armed) groups and other users for illicit purposes.

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
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 December 2021
Luis Merino	Universidad Pablo de Olavide	27 January 2022
Interviewee K	–	1 February 2022
Interviewee I	–	1 February 2022
Interviewee J	–	1 February 2022
Interviewee L	–	3 February 2022

34 Interviews with Geert de Cubber (27/10/2021), Chief Engineer, Trusted Autonomous Systems (21/12/2021); anonymous interviewee D (15/12/2021).
35 Hassanalian & Abdelkefi (2017).
36 Interviews with anonymous interviewees I and J (01/02/2021).
37 Tucker (2021); Interview with Chief Engineer, Trusted Autonomous Systems (21/12/2021).

REFERENCES

Amer, K., Samy, M., Shaker, M. & M. ElHelw. 2019. "Deep convolutional neural network-based autonomous drone navigation." *ArXiv*.

Berie, H.T. & I. Burud. 2018. "Application of unmanned aerial vehicles in earth resources monitoring: Focus on evaluating potentials for forest monitoring in Ethiopia." *European Journal of Remote Sensing* 51(1).

Boukoberine, M.N., Zhou, Z. & M. Benbouzid. 2019. "A critical review on unmanned aerial vehicles power supply and energy management: Solutions, strategies, and prospects." *Applied Energy* 255(113823).

Deppe, T. & J.N. Munday. 2019. "Nighttime photovoltaic cells: Electrical power generation by optically coupling with deep space." *ACS Photonics* 7(1): 1–9.

Di Luca, M., Mintchev, S., Heitz, G., Noca, F. & D. Floreano. 2017. "Bioinspired morphing wings for extended flight envelope and roll control of small drones." *Interface Focus* 7.

Dilmegani, C. 2022. "AI chips: A guide to cost-efficient AI training & inference in 2022." *AI Multiple*, 9 February.

Dorsey, J. & N. Amaral. 2021. *Military Drones in Europe: Ensuring Transparency and Accountability*. Chatham House Research Paper, International Security Programme, April.

Drexel University. 2022. "Breakthrough in cathode chemistry clears path for lithium–sulfur batteries' commercial viability." *Drexel News*, 10 February.

Falanga, D., Kleber, K., Mintchev, S., Floreano, D. & D. Scaramuzza. 2019. "The foldable drone: A morphing quadrotor that can squeeze and fly." *IEEE Robotics and Automation Letters* 4(2): 209–216.

Ferreira, A.D.B.L., Nóvoa, P.R.O. & A.T. Marques. 2016. "Multifunctional material systems: A state-of-the-art review." *Composite Structures* 151: 3–35.

Giordan, D., Adams, M.S., Aicardi, I. et al. 2020. "The use of unmanned aerial vehicles (UAVs) for engineering geology applications." *Bull. Eng. Geol. Environ*. 79 3437–3481.

Gong, A., Palmer, J.L. & D. Verstraete. 2018. "Flight Test of a fuel-cell/battery/supercapacitor triple hybrid UAV propulsion system." *31st Congress of the International Council of the Aeronautical Sciences*.

Haider, A. 2020b. "Unmanned aircraft system threat vectors." In M. Willis, A. Haider, D.C. Teletin & D. Wagner (Eds). *A Comprehensive Approach to Countering Unmanned Aircraft Systems* (pp. 33–52). The Joint Air Power Competence Centre.

Hang et al. 2019. "Perching and resting—A paradigm for UAV maneuvering with modularized landing gears." *Science Robotics* 4.

Hassanalian, M. & A. Abdelkefi. 2017. "Classifications, applications, and design challenges of drones: A review." *Progress in Aerospace Sciences* 91:99–131.

Honeywell. 2021. "Honeywell to bring next-generation inertial sensors to unmanned vehicles segment." *Honeywell*, 25 January.

Irving, M. 2021. "Bipedal robot/drone hybrid can walk, fly and skateboard." *New Atlas*, 6 October.

Krähenmann, S & G. Dvaladze. 2020. "Humanitarian concerns raised by the use of armed drones." Geneva Call, 16 June.

Khan, S.M. & A. Mann. 2020. *AI Chips: What They Are and Why They Matter*. Center for Security and Emerging Technology.

Li, B., Gu, J. & W. Jiang. 2019. "Artificial intelligence (AI) chip technology review," *2019 International Conference on Machine Learning, Big Data and Business Intelligence (MLBDBI)*, pp. 114–117.

Michel, A.H. 2019. *Counter-drone Systems*. Center for the Study of the Drone at Bard College.

Noda, R., Nakata, T., Ikeda, T., Chen, D., Yoshinaga, Y., Ishibashi, K., Rao, C. & H. Liu. 2018. "Development of bio-inspired low-noise propeller for a drone," *J. Robot. Mechatron*. 30(3): 337–343.

Office for Disarmament Affairs. 2015. Study on *Armed Unmanned Aerial Vehicles: Prepared on the Recommendation of the Advisory Board on Disarmament Matters*. United Nations: New York.

Santana, G.M.D., Silva de Cristo, R. & K.R.L.J. Castelo Branco. 2021. "Integrating cognitive radio with unmanned aerial vehicles: An overview." *Sensors* 21(3): 830.

Sayler, K. 2015. *A World of Proliferated Drones: A Technology Primer*. Center for a New American Security.

Siadkowska, K. 2021. "Smart materials technologies in composite structures of aerial vehicles." *AIP Conference Proceedings* 2429 (020035).

Tucker, P. 2021. "Quantum sensor breakthrough paves way for GPS-free navigation." *Defense One*, 2 November.

UAS Task Force Airspace Integration Integrated Product Team. 2011. *Unmanned Aircraft System Airspace Integration Plan*. US Department of Defense.

Wellers, D. & F. Fitter. N.d. "6 surprising innovations for the future of computing." SAP.

Woodhams, G. & J. Borrie. 2018. *Armed UAVs in Conflict Escalation and Inter-state Crisis*. UNIDIR.

Yaacoub, J-P., Noura, H., Salman, O. & A. Chehab. 2020. "Security analysis of drones systems: Attacks, limitations, and recommendations." *Internet of Things* 11:100218.

Zeng, Y., Gordiichuk, P., Ichihara, T. et al. 2022. "Irreversible synthesis of an ultrastrong two-dimensional polymeric material." *Nature* 602, 91–95.

Zwijnenburg, W. & F. Postma. 2018. *Unmanned Ambitions: Security Implications of Growing Proliferation in Emerging Military Drone Markets*. PAX.

Acknowledgements

Support from UNIDIR core funders provides the foundation for all of the Institute's activities. This joint report produced by the Conventional Arms and Ammunition Programme and the Security and Technology Programme of UNIDIR recognizes the growing impact of technological advances on conventional arms. The preparation of this report has been supported by generous funding for the Conventional Arms and Ammunition Programme by Germany and for the Security and Technology Programme by Germany, the Netherlands, Switzerland and Microsoft.

The authors wish to thank the experts who participated in interviews and provided valuable inputs during the course of the research. The authors are also grateful to the experts who reviewed and provided valuable inputs to the report: Geert De Cubber, Simon Ng, Paul Holtom, Giacomo Persi Paoli, Hardy Giezendanner, Ioana Puscas, Barbara Morais Figueiredo and Ruben Nicolin.

About UNIDIR

The United Nations Institute for Disarmament Research (UNIDIR)—an autonomous institute within the United Nations—conducts research on disarmament and security. UNIDIR is based in Geneva, Switzerland, the centre for bilateral and multilateral disarmament and non-proliferation negotiations, and home of the Conference on Disarmament. The Institute explores current issues pertaining to a variety of existing and future armaments, as well as global diplomacy and local tensions and conflicts. Working with researchers, diplomats, government officials, NGOs and other institutions since 1980, UNIDIR acts as a bridge between the research community and Governments. UNIDIR activities are funded by contributions from Governments and donor foundations.

Authors

Sarah Grand-Clément is a Researcher in the Conventional Arms and Ammunition Programme and the Security and Technology Programme at UNIDIR. Theò Bajon is an Associate Researcher in the Conventional Arms and Ammunition Programme at UNIDIR.

UNIDIR UNITED NATIONS INSTITUTE FOR DISARMAMENT RESEARCH

www.unidir.org @unidirgeneva @UNIDIR un_disarmresearch