UNCREWED GROUND SYSTEMS: A PRIMER

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SUMMARY OF KEY POINTS

- Uncrewed ground systems (UGSs) can be distinguished by two main characteristics: (a) their size and weight and (b) their locomotion type. They can range from small, handheld models to large, tank-sized models, while their locomotion types primarily include wheeled, tracked and legged models. These characteristics have an impact on the capabilities of the system – such as the type of terrain it is best suited to, its speed and its ability to carry a substantial payload – and what tasks it is best suited to undertake. Overall, civilian UGSs tend to be smaller than military UGSs.
- The limitations faced by UGSs due to their mobility challenges and reliance on GNSS, which affects their ability to operate in GNSS-denied environments, has restricted their use. Thus, UGSs have posed few threats to international security, particularly compared to their aerial equivalents. However, there is increased interest in developing and deploying UGSs within the military domain, which could, in future, lead these systems to posing a greater threat to international security.
- UGSs are faced with several technical challenges that have hampered their greater use. Ongoing areas for improvement include locomotion and propulsion to improve their useability and endurance, as well as sensors, artificial intelligence and computing power to enable navigational autonomy.

INTRODUCTION

The development of uncrewed ground systems (UGSs) – which include vehicles that can be piloted either remotely or semi-autonomously – is increasing. The term UGS encompasses both the vehicle (the uncrewed ground vehicle, UGV) and the control system that enable 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 aerial systems (UASs) 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 UGS, 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 UGSs, 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.

DIFFERENT TYPES OF UGS

There is no universal classification of UGSs. UGSs can be differentiated according to whether or not they are armed and characteristics such as size and weight. For example, systems can range from small, handheld models to large, tank-sized models. Another characteristic to differentiate UGSs is type of locomotion.[1] There are three main types:

- **Wheeled:** Wheels are the most power-efficient locomotion type. However, wheels are less suited for off-road terrain.
- **Tracked:** Tracks are well suited for use off-road but are noisy, consume a lot of power and operate at low speeds.
- **Legged:** Legged systems can manoeuvre rough terrain well. However, they are generally slow, require more power than wheels or tracks, and are 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.

While large armed wheeled or tracked systems can carry substantial firepower, armed legged systems are only able to carry smaller weapons, such as adapted small arms. Additionally, certain UGSs can combine two types of locomotion, such as wheels and legs, enabling them to cover a wider variety of terrains and overcome some of the limitations linked to individual locomotion types.

While there are different types of UGS, 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 systems can have wheeled or tracked vehicles) and the type of technology used to power and navigate these systems. Some of the techno logies and areas of innovation that pertain to uncrewed systems can also apply to crewed systems – and vice versa. The main differences relate to the fact the crewed ground systems have a driver and crew on board the vehicle, unlike UGVs, 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 operators controlling some or all of its functions.

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

There are additional differences related to whether a ground platform has someone onboard. Some are physical: for example, without a driver and crew in a vehicle, space becomes available for other features or payload. Additionally, the risk to the life of the UGS operator is lowered or even removed compared to that of a vehicle's driver and crew if the UGV is attacked. This difference is also notable in relation to the types of task that crewed and uncrewed systems can undertake. For example, uncrewed systems can be used for more dangerous activities, such as demining and dealing with improvised explosive devices (IEDs).

1 Odedra et al. (2009); Gonzalez-De-Santos et al. (2020); Demaitre (2021).

FUNCTIONS OF A UGS

UGSs are being developed for military and civilian use. Figure 1 shows there are some functions that differ depending on user, but also where there are areas of commonality, such as for logistics, even if the items being transported differ. For example, military UGSs will primarily aim to help with resupply and goods delivery, whereas civilian UGSs will be primarily used to aid with agriculture or mining.

Figure 1: Functions of UASs in the military and civilian domains[2]

Military functions	Military and civilian functions	Civilian functions
> Chemical, biological, radiological and nuclear (CBRN) detection > Target acquisition > Strike operations (if armed) > Supporting platform (e.g., provision of power to uncrewed aerial systems, communication relay) > Weapon detection and disposal (e.g., mine clearing and IED search-and-destroy)	> Logistics and logistical support > Monitoring, intelligence, surveillance and reconnaissance > Search and rescue	> Hobbyist use > Commercial use

CURRENT CHALLENGES TO INTERNATIONAL SECURITY

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. UGSs are not widespread in the civilian domain and their use in the military domain is mainly for detecting and disposing of weapons such as mines and IEDs. However, in the military domain, there is an increased focus on developing UGSs that can navigate autonomously and UGSs that are armed. This could lead to them posing challenges to international security such as those in the following, non-exhaustive list:

- **Change to the threshold for the use of force:** As with other types of uncrewed system, military UGSs could lower the threshold for the use of force given their ability to distance personnel from risk. This has led to claims that this could incentivise armed hostilities or conflict.[3]
- **Increased lethality:** Large wheeled and tracked systems can carry a significant payload, including heavy armament.[4] In addition, they can be equipped to work jointly with armed or unarmed UASs, with a UGS for example being used as a launchpad for a UAS.[5] If armed (or equipped with an armed UAS), a UGS would be able to project firepower in addition to providing intelligence, surveillance and reconnaissance.[6]
- **Ethical and legal challenges:** The use of lethal UGSs can pose challenges to the interpretation and application of international humanitarian law and international human rights law, particularly if used without proper legal constraints. For example, the use of such systems by law enforcement could lead to a militarisation of police forces as well as to legal and regulatory questions around whether and how to enable and approve of the use of lethal force by a UGS.[7]

2 Autonomous cars are not included because, even though they are uncrewed in the sense that they do not have a driver or an operator, their aim is to transport passengers and as such they are not unoccupied. Nonetheless, it should be noted that certain technological developments that apply to UGSs also apply to autonomous cars and vice versa, particularly in the field of increasing autonomous navigation.
3 Office for Disarmament Affairs (2015); Woodhams & Borrie (2018).
4 Interview with Luis Merino (27/01/2022).
5 Balestrieri et al. (2021).
6 Scharre (2014); Martinic (2014).
7 Joh (2016); Sullivan et al. (2016).

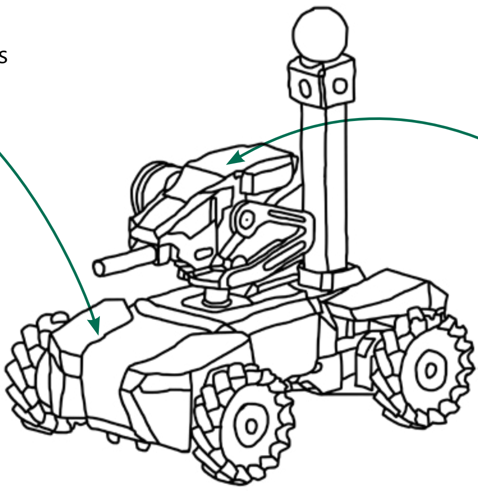
- **Exploitation of system vulnerabilities:** UGSs are also vulnerable to interference, such as by jamming, hacking or otherwise disrupting the data links between remotely controlled systems and their operators. This includes the spoofing of the system's perception ability, such as by tricking the vehicle's sensors into detecting fake obstacles or by manipulating its image-recognition component, thereby interfering with the ability to navigate a UGV safely.[8] Such interference could also affect the communications systems and data being sent between the vehicle and the operator, in turn also affecting the ability to navigate the system.[9] 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 soft targets.[10]
- **Proliferation and misuse:** UGSs and their underlying technology will continue to become increasingly accessible and affordable, particularly as the technologies enabling UGSs (e.g., AI, sensors) continue to improve. Such technologies can also "autonomise" navigation and therefore convert crewed vehicles to being able to operate without a crew.[11] As with other types of uncrewed system, it is likely that the systems and technologies available to both states and non-state actors will proliferate.[12] This could lead to the use, or increased use, of these systems to conduct attacks, via vehicular attacks, use of vehicle-borne IEDs or by mounting weapons onto a UGV. Despite increased access to advanced technology, it should nonetheless be noted that there exists and will continue to exist a significant divergence in the technology used across different systems, ranging from very high-end to very low-end systems.

KEY COMPONENTS OF A UGS

Most UGSs 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.

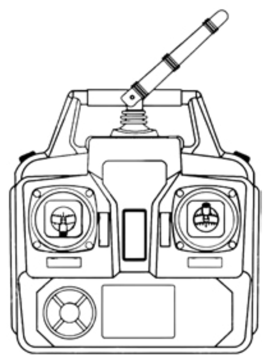
Figure 2: Key components of a UGS

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



The **payload** refers to additional components which can be carried by the UGS but are essential to its operability. Both civilian and military vehicles can incorporate a payload. This can include additional sensors (beyond those needed for navigation), goods (e.g., medical supplies or food), or weapon systems.

The **remote-control system** refers to the communications with the system and its remote navigation. The remote-control system can vary in complexity depending on the type of UGS 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)

8 See for example Petit et al. (2015).
9 Scharre (2014); Tutunji et al. (2020); Bērziņš (2016); Rossiter (2020).
10 Yaacoub et al. (2021).
11 Blagoeva et al. (2020).
12 Rossiter (2020); Izadi Moud et al. (2018); Balestrieri et al. (2021); Martinic (2014).

AREAS OF INNOVATION

UGSs are faced with several technical challenges that have hampered the greater use of such systems to date. For example, UGSs face navigational challenges in unknown, unstructured or unpredictable environments and difficult, obstructed or uneven terrain, in addition to having to deal with issues such as dirt, mud, dust or rain.[13] UGSs are also technically complex to build and use, given that they require a high level of energy to operate.[14]

The technological innovations outlined below include developments that are specific to UGSs 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 – including its shape, structure and material – encompasses the "skeleton" of the UGV, meaning the hardware comprising the body of the system. Of particular importance here is the categorisation of systems according to their domain (i.e., air, ground or maritime) as they may become outdated as a result of innovations regarding cross-domain capabilities.

The main areas of innovation include:

- **Cross-domain systems:** There are developments to enable UGSs to operate across the land, sea and air domains. For example, amphibious systems already exist, while there are also small-sized ground systems with the ability to fly.[15] 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, including within arms control processes.
- **Range of locomotion types:** Research continues to seek new and different forms of locomotion to overcome existing challenges with regards to terrain and other obstacles. For example, legged systems of various types (e.g., bipedal and quadrupedal) are likely to become more common since they are better suited to challenging terrain. However, their increased use also comes with security challenges due to their limited ability to carry a lethal payload.[16] These systems are being joined by other less common types of locomotion that mimic animals or insects, such as snake-like UGVs, which would be better able to navigate difficult terrain and operate in space-constrained environments.[17]
- **Advanced materials:** Research is progressing to develop advanced materials which comprise the structure or frame, or coat the structure of a UGV, which could create lighter yet sturdier and more resistant UGVs. For example, there is research into the use of materials that have a greater resistance to shocks, such as the impact of bullets.[18] Advanced materials could also integrate self-healing properties, mimicking biological organisms, with research ongoing to develop these.[19]

Power source and means of propulsion

A UGV can be powered by, for example, fuel or renewable energy. Of particular importance here is that innovations aim to further improve the endurance of UGSs. Longer performance capabilities could make the use of UGSs more appealing in military operations.

The main areas of innovation include:

- **Battery advances:** Certain smaller UGVs are battery-powered, while batteries also play an important role in powering electronic systems in larger UGVs. Lithium batteries are the most commonly used today.[20] 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 UGVs, in particular those which are battery-powered, as well as the endurance of the electronics embedded within the systems. A higher endurance would mean that a UGS could be operational for longer periods of time.
- **Other types of power source and propulsion method:** Other types of power source include jet fuel or propane, as well as internal combustion engines. Efforts are underway to increase the reliability, reduce the costs and acoustic signature, and improve the power and energy management of such methods.

13 Rossiter (2020); Balestrieri et al. (2021); Odedra et al. (2009); Interview with Nick Reynolds (12/11/2021).
14 National Research Council (2005); Balestrieri et al. (2021).
15 For example: Irving (2021).
16 Interview with anonymous interviewee D (15/12/2021).
17 Evans (2013).
18 Trafton (2022).
19 For example: Tan et al. (2020).
20 See for example a new breakthrough in lithium-sulphur batteries: Drexel University (2022).

Communication system

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

The main areas of innovation include:

- **Optical communications:** Developments in this area include the use of optical wireless communication as an alternative to radio frequency (RF) communication technology. This also enables navigation beyond the visual line of sight (i.e., when the UGS operator can no longer see the UGV without technological support). Optical communications could also potentially form the basis of sixth-generation (6G) communication systems, enabling even faster data transmission through increased bandwidths, while not being prone to RF interference (e.g., signal jamming).
- **Antenna innovations:** UGSs use antennas to transmit and receive data, or even act as a communication relay. They are thus critical for UGSs, including those that do not integrate autonomous navigation features. Novel antenna designs and innovations around different antenna types (e.g., to increase signal strength) are being integrated into UGSs.

Electronics and sensors

The electronic elements and sensors embedded in a UGS enable it to perform functions such as navigation and decision-making. Of particular importance here is research seeking to ensure that UGVs can increasingly navigate autonomously. This reduces, or may even completely remove, the role of the remote operator, thus increasingly reducing human control while also enabling UGVs to function autonomously in complex or congested 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. They are key in areas with no global navigation satellite system (GNSS) signal or to reduce the dependence of the UGS on GNSS.[21] A range of sensors aid UGS navigation, along with AI and computing power. There is constant research to develop and improve sensors, such as radar sensors, to ensure redundancy, higher resolution data collection and more accuracy for navigational purposes.[22] 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.[23] Additional innovations could also help UGSs to better recognise different terrains and adapt their locomotion accordingly. These developments aim to improve UGS navigation capability, as well as to enable more autonomous navigation.
- **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 UGVs and thus the precision of their navigation.[24]

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 UGV 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. AI for navigational autonomy is of particular importance to enable the increased use of UGSs, given the more complex and congested land environment, particularly in urban areas.[25]
- **Computing power:** Semiconductors and 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 UGV.
- **Robotic teaming:** Robotic teaming, or collaboration to complete a task, including between systems across different domains, will continue to improve.[26] This includes swarming-type technology, where a number of systems are deployed at once, although true swarming still remains further into the future.

21 Interview with anonymous interviewee E (11/11/2021).
22 Interviews with anonymous interviewees E (11/11/2021) and K (01/02/2022), and with Luis Merino (27/01/2022) and Bruno Martens (02/12/2021).
23 Interview with Bruno Martens (02/12/2021).
24 Interview with Geert de Cubber (27/10/2021).
25 Interviews with Nick Reynolds (12/11/2021) and anonymous interviewee F (15/12/2021).
26 Interview with Chief Engineer, Trusted Autonomous Systems (21/12/2021).

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

Box 2: Additional areas of innovation

Electronics and components of all types are **becoming increasingly miniaturised**, simultaneously becoming more powerful and, in some cases, cheaper.[27] This includes, for example, making smaller chips and sensors but also smaller propulsion solutions, such as fuel cells, driven by innovations in the field of nanotechnology, such as nanomaterials. This trend means that smaller systems may be just as smart and capable as larger ones, whereby size is no longer an indication of capability. This may have an impact on arms control categorisations.

While the use of **quantum technology** in everyday occurrences still remains a rather distant possibility, its various uses are expected to lead to vast changes. For example, quantum computing will greatly increase the speed of data processing. Quantum communications (i.e., quantum key distribution) is expected to create secure channels of communication as well as enable a higher level of encryption and decryption and a faster decision-making process.[28] Quantum sensors would, for example, remove the need to rely on GNSS for navigation.[29]

CONCLUDING REMARKS

Specific types of remote-controlled uncrewed ground system are already in use, and have been for some time already, such as UGSs used for demining purposes. However, overall, the development and use of UGSs have been more limited than their aerial or maritime counterparts due to two main factors. The first relates to their mobility and ability to direct themselves and overcome difficult terrain. The second factor is the significant reliance of UGSs on GNSS, which affects their ability to operate in GNSS-denied environments. However, innovations in the civilian domain regarding computing, processing power and energy as well as commercial incentives towards operationalising vehicles that can navigate autonomously will, and to some extent already have, permeated to the military domain and into military UGSs.

More generally, UGSs are considered an asset in conflict situations as they can help further project firepower, provide lethal and non-lethal support to military personnel, and aid in further distancing personnel from the battlefield. Improved locomotion abilities and navigational autonomy are notable areas of innovation that will have an impact on system capability. As a result, this could lead to increased use of UGSs as well as improved military capabilities, which in turn could have an impact in terms of the attitude towards, and appetite for, direct engagement. Beyond the military domain, civilian UGSs could present a risk depending on the user and the intended purpose. These mobile civilian UGSs can be small and have limited sophistication, but still pose a threat. Nonetheless, the navigation element remains a constraint, particularly in less advanced systems.

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
Geert de Cubber	Belgian Royal Military Academy	27 October 2021
Interviewee E	–	11 November 2021
Nick Reynolds	RUSI	12 November 2021
Bruno Martens	UNICRI	2 December 2021
Interviewee D	–	15 December 2021
Interviewee F	–	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

27 Interviews with Geert de Cubber (27/10/2021); Chief Engineer, Trusted Autonomous Systems (21/12/2021) and anonymous interviewee D (15/12/2021).
28 Interview with anonymous interviewee I and J (01/02/2022) and F (15/12/2021).
29 Tucker (2021); Interview with Chief Engineer, Trusted Autonomous Systems (21/12/2021).

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