OFF THE LEASH

The development of autonomous military drones in the UK

Note: The term 'drone' is used interchangeably with 'Unmanned Aerial Vehicle (UAV)'

Drone Wars UK is a small British NGO established in 2010 to undertake research and advocacy around the use of armed drones. We believe that the growing use of remotely-controlled, armed unmanned systems is encouraging and enabling a lowering of the threshold for the use of lethal force as well as eroding well established human rights norms. While some argue that the technology itself is neutral, we believe that drones are a danger to global peace and security. We have seen over the past decade that once these systems are in the armoury, the temptation to use them becomes great, even beyond the constraints of international law. As more countries develop or acquire this technology, the danger to global peace and security grows.

Executive summary

Unmanned Aerial Vehicles (UAVs), commonly known as drones, are likely to be the military system which develops into the first truly autonomous weapons systems. Powered by advances in artificial intelligence (AI), machine learning, and computing, we are likely to see the development not only of drones that are able to fly themselves – staying aloft for extended periods – but those which may also be able to select, identify, and destroy targets without human intervention. In many ways, the increasing use of remote controlled, armed drones can be seen as a kind of 'halfway house' towards the development of truly autonomous weapon systems. The incremental way in which drone technology is developing, and the ability to 'bolt on' new features, means that drones are ideally suited to morph into autonomous weapon systems.

This study looks at current initiatives which are under way in the UK to marry developments in autonomy with military drone technology, examines the risks arising from the weaponisation of such systems, and reviews government policy in this area. Autonomous weapon systems are defined using the definition proposed by International Committee of the Red Cross (ICRC) as: "Any weapon system with autonomy in its critical functions – that is, a weapon system that can select and attack targets without human intervention."

Two separate uses for AI and autonomous technology are becoming increasingly important in the military world. Firstly, autonomous systems can be used to process and analyse large amounts of raw intelligence information in order to find targets. Secondly, AI can be incorporated into the weapons themselves as well as to execute operational missions.

The extent to which autonomy within a drone raises concerns will depend upon the level of human control over the targeting and launch of weapons and the use of force in general. Although existing armed drones have a degree of autonomy in some of their functions – for instance in relation to flight control – at present human control is maintained over the use of force, and so today's armed drones do not qualify as fully autonomous weapons. Many question whether systems with the capability to make autonomous targeting decisions would be able to comply with the laws of war.

Our research has found that a number of public organisations, private companies, and government agencies in the UK are involved in undertaking research and development work into autonomous technology, AI and drones. The Ministry of Defence (MoD) sees autonomous technology and data science as "key enablers" for the future, and the Defence Science and Technology Laboratory (DSTL) and its Defence and Security Accelerator programme have extensive research programmes in this field.

The Engineering and Physical Sciences Research Council (EPSEC), too, is a significant funder of research in these areas and a number of universities are working on autonomous technology programmes with military applications, often in collaboration with private sector military contractors.

Investment and innovation in artificial intelligence is being led by the civil sector and not by the world's militaries. Autonomous technologies, originating in the civil sector but adapted for military applications, are likely to become key components of the autonomous drones and weapons of the future. Military planners are aware of the civil sector's lead in developing artificial intelligence and autonomous systems and are keen to have a slice of the cake.

Although the military technology research sector is smaller than its civil counterpart and has fewer resources, it is in a position to adapt existing military systems and is adept at anticipating military needs and pursuing military contracts. The Ministry of Defence's favoured contractors for work on drones and autonomous systems appear to be BAE Systems, QinetiQ, and the Thales Group. BAE Systems, for example, has built 'Taranis', an advanced prototype autonomous stealth drone.

Current Ministry of Defence policy states that the UK opposes the development of autonomous weapon systems and has no intention of developing them. However, the Ministry of Defence has been accused of a sleight of hand here by defining autonomous weapons systems differently from other governments and institutions. Although the UK states that it has "no intention" of developing such systems, this does not sit comfortably alongside endorsements for autonomous weapons from senior members of the UK armed forces. The claim that "the UK opposes the development of armed autonomous systems" also appears to be at odds with the evidence. Since 2015, the UK has declined to support moves at the United Nations Convention on Certain Conventional Weapons aimed at banning autonomous weapon systems.

As a nation which considers itself a responsible and leading member of the international community, the United Kingdom has a duty to use its influence and powers to ensure that the weapons of the future are never used outside boundaries set by the laws of humanity and the requirements of the public conscience. Our recommendations are summarised as:

- The UK should support the introduction of a legal instrument to prevent the development, acquisition, deployment, and use of fully autonomous weapons.
- The UK should make an unequivocal statement that it is unacceptable for machines to control, determine, or decide upon the application of force in armed conflict and give a binding political commitment that the UK would never use fully autonomous weapon systems.
- The UK should introduce measures to ensure that human control must be exerted over all attacks in armed conflict.
- The government should realign the UK's definition of autonomous weapons to be the same, or similar, as that used by the rest of the world.
- The government should publish an annual report identifying research it has funded in the area of military autonomous technology and artificial intelligence.
- MPs and Peers should investigate the impact of emerging military technologies, including autonomy and artificial intelligence, and press the government to adopt an ethical framework.
- The government should fund a wide-ranging study into the use of artificial intelligence to support conflict resolution and promote sustainable security.
- The government should initiate a broader public debate on the ethics and future use of artificial intelligence and autonomous technologies, particularly their military applications.

1 Introduction

Drones: a gateway to autonomous weapon systems

Military planners have a long history of taking advantage of technological developments to aid war-fighting. Shortly after the very first heavier-than-air aircraft flight by Orville and Wilbur Wright, aircraft were rapidly identified as weapons of war.[1] Likewise, the first modern programmable computers were developed for use in wartime: the 'Colossus' computers at Bletchley Park assisted in breaking German codes during World War II, while at around the same time design and construction of the 'ENIAC' computer was financed by the US Army to support its ballistics research.[2]

Although today's aircraft and computers have developed almost beyond recognition from those first models, it should come as no surprise that new combinations of these technologies are of great interest to the world's militaries. While drones have become familiar over recent years, the next technological leap – powered by advances in artificial intelligence (AI), machine learning, and advanced computing – is likely to see the development not only of drones that are able to fly themselves and stay aloft for extended periods, but those which may also be able to select, identify, and destroy targets without human intervention.

This report focuses particularly on the development of such technology within the UK. It:

- Identifies key technologies influencing the development of future armed drones and drivers for the development of lethal autonomous drones.
- Identifies the current state of play in relation to autonomy within systems currently deployed and under development for the UK military.
- Identifies agencies, laboratories, and contractors undertaking research into drones and autonomous weapon technology in support of the UK Ministry of Defence.
- Identifies risks arising from the development of autonomous weapon systems.
- Makes recommendations on measures the UK can take to help prevent the development of lethal, fully autonomous armed drones.

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1 Nitant Narang: 'How the Wright Brothers Went Wrong'. Procurify blog. https://blog.procurify.com/2016/08/10/wright-brothers-went-wrong-with-procurement/
2 'How computers changed the Second World War and digital communications'. BBC Bitesize. https://www.bbc.co.uk/education/clips/z98hfg8

Section 2 of this report briefly examines what is meant by machine autonomy, looks at the pros and cons of various models used to discuss the development of autonomous weapon systems and asks what is driving the development of autonomy in the military arena.

While 'fully autonomous' weapon systems do not yet exist, some military systems already in service have highly automatic or autonomous components. Some of today's armed drones, for example, while described as 'remotely controlled,' can have autonomous capabilities, such as take-off and landing, navigation, and software updating. The incremental way in which drone technology develops, and the ability to 'bolt on' new features, means that drones are ideally suited to morph into autonomous weapon systems. However, the extent to which autonomy within a drone raises concerns will depend upon the level of human control over the targeting and launch of weapons and the use of force in general. Section 3 of our report breaks down the various elements of an armed drone and examines in detail the current capabilities of each of these 'building blocks' and the prospect for further autonomy in each area.

While research is underway in a number of countries that would enable the development of lethal autonomous drones, the heart of this report is a survey of the research that is currently under way within the UK. Section 4 identifies research and development work that is taking place in a number of public organisations, private companies, and government agencies into autonomous technology, artificial intelligence and drones. In addition, we set out in four case studies specific examples of developments in this area. The Ministry of Defence is clear that it sees autonomous technology and data science as "key enablers" for the future, and its Defence Science and Technology Laboratory and its Defence and Security Accelerator programme have extensive research programmes in this field.

> Letting machines 'off the leash' and giving machines them the ability to take life crosses a key ethical and legal Rubicon

The final part of our report examines the dangers posed by marrying highly complex autonomous technology with lethal force applications and the UK government's position. Drone Wars UK is clear that the development and deployment of lethal autonomous drones would give rise to a number of grave risks, primarily the loss of humanity and compassion on the battlefield. Letting machines 'off the leash' and giving machines them the ability to take life crosses a key ethical and legal Rubicon. Autonomous lethal drones would simply lack human judgment and other qualities that are necessary to make complex ethical choices on a dynamic battlefield, to distinguish adequately between soldiers and civilians, and to evaluate the proportionality of an attack. Other risks from the deployment of autonomous weapons include unpredictable behaviour, loss of control, 'normal' accidents, and misuse.

We end our report with several recommendations intended to urge the UK government to use its influence and powers to ensure that the weapons of the future are never used outside the boundaries set by the laws of humanity and the requirements of the public conscience (as stipulated in the 'Martens Clause').[3] Lethal autonomous drones should neither be developed nor deployed.

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3   Rupert Ticehurst: 'The Martens Clause and the Laws of Armed Conflict'. International Review of the Red Cross, no.317. 30 April 1997. https://www.icrc.org/eng/resources/documents/article/other/57jnhy.htm

Excellent studies in the area of autonomous weapons have recently been published by the by International Committee of the Red Cross,[4] the United Nations Institute for Disarmament Research,[5] and the Stockholm International Peace Research Institute,[6] analysing the consequences of developing autonomous weapon systems. This study draws on these sources but does not seek to replicate them, and interested readers are recommended to consult them.

BAE Systems' Taranis stealth drone is able to fly itself and features a number of autonomous systems.
Credit Crown Copyright

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4   International Committee of the Red Cross: 'Autonomous Weapon Systems: Technical, Military, Legal and Humanitarian Aspects'. Report of Expert Meeting, 26-28 March 2014, Geneva, Switzerland. https://www.icrc.org/en/download/file/1707/4221-002-autonomous-weapons-systems-full-report.pdfInternational Committee of the Red Cross: 'Expert Meeting. Autonomous Weapon Systems: Implications of Increasing Autonomy in the Critical Functions of Weapons'. Versoix, Switzerland, 15-16 March 2016. https://shop.icrc.org/autonomous-weapon-systems.html?___store=default

5   United Nations Institute for Disarmament Research (UNIDIR): 'Framing Discussions on the Weaponization of Increasingly Autonomous Technologies'. 2014. http://www.unidir.org/files/publications/pdfs/framing-discussions-on-the-weaponization-of-increasingly-autonomous-technologies-en-606.pdf See also associated publications at http://bit.ly/UNIDIR_Autonomy

6   Vincent Boulanin: 'Mapping the development of autonomy in weapon systems. A primer on autonomy'. Stockholm International Peace Research Institute Working Paper, December 2016. https://www.sipri.org/publications/2016/other-publications/mapping-development-autonomy-weapon-systems
Vincent Boulanin and Maaike Verbruggen: 'Mapping the development of autonomy in weapon systems'. Stockholm International Peace Research Institute, November 2017. https://www.sipri.org/publications/2017/other-publications/mapping-development-autonomy-weapon-systems

A brief introduction to autonomous technology

How autonomy and artificial intelligence are transforming warfare

One of the key reasons drones have hit the headlines in recent years is the controversy over their use to launch military attacks – particularly so-called 'targeted killings' – from great distance. However, the drones used to undertake such attacks are piloted remotely by humans who are in direct control of the aircraft and its weapons. Today's drones have relatively few automated features, but future systems are expected to have the capability to operate entirely autonomously and perhaps even be able to make their own decisions on identifying, selecting, and destroying targets without human intervention. This raises grave ethical, legal, and safety issues and creates significant risks for global peace and security.

2.1 What is autonomy?

Autonomy in machines relies on technology from a number of disciplines, but the most important of these is computer software.[7] As processing power expands and computers become more powerful, mathematical approaches combining large numbers of algorithms can be used to solve complicated problems and mimic cognitive functions such as learning, planning, and perception. Computers are already able to routinely recognise characters and images optically, understand human speech, and in certain limited circumstances control driverless cars. In the future, it is anticipated that they may be able to reason and 'deep learn' as artificial intelligence systems, and develop a general intelligence that allows them to undertake any intellectual task that a human can – or even beyond.[8]

Developments in autonomous technology are often presented as being focused on undertaking 'dull, dirty, or dangerous' tasks, but increasing computing

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7   'Task Force Report: The Role of Autonomy in DoD Systems'. Department of Defense Defense Science Board, July 2012. https://fas.org/irp/agency/dod/dsb/autonomy.pdf

8   Artificial intelligence has been defined in different ways by different authors, but one useful definition is 'the automation of activities that we associate with human thinking, activities such as decision-making, problem solving, learning...' R.E. Bellman: 'An Introduction to Artificial Intelligence: Can Computers Think?'. Body and Fraser Publishing Company, San Francisco, 1978.

capabilities and the advent of artificial intelligence now open the prospect that autonomous weapon systems will eventually undertake much more complex operations. To be able to act autonomously, a weapon system must be able to sense its environment, make a decision, and then take action towards achieving an objective. To be able to sense the external environment, the system must use a sensor such as a video camera to collect data, and then process and interpret that data. Software enables the system to make decisions.

Machine learning – giving computers the ability to learn without being explicitly programmed – has begun to rapidly develop of the over the last few years. Machine learning allows a software system to be developed which is capable of learning by itself, and then 'training' it to make a desired decision. However, this process requires very large quantities of data. Computers learn by identifying statistical relationships in data, and to be taught they need to be provided with large numbers of real-world examples as training data. For many of the military tasks which autonomous weapons might be required to undertake, including targeting, this is a problem, as there is a lack of high-quality data sets.[9] The smaller the data set used to train computers the greater the risk of erroneous decision-making.

Such systems are able to learn rapidly, with or without human-supplied training data, and devise novel strategies radically different to human approaches to solving problems.[10] Machine learning and cloud robotics (the ability of individual robots to learn from the experiences of all robots in a group, resulting in a rapid growth in competence) are expected to become key enabling technologies for the future of autonomous drones and weapon systems.

The Phalanx close-in weapons system is a highly automated system for defending ships against missile and aircraft attacks. **Credit** William Weinert, US Navy

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9   Vincent Boulanin and Maaike Verbruggen: 'Mapping the development of autonomy in weapon systems', op cit. P17.

10   Alan Bellows: 'On the Origin of Circuits'. Damninteresting.com, 27 June 2007. https://www.damninteresting.com/on-the-origin-of-circuits/

2.2 Marrying lethal autonomy and drones

By combining modern computing capabilities with robotics and miniaturisation technology it is now technically feasible, some scientists say, to develop fully autonomous weaponised drones which could make their own decisions on targeting and firing. In testimony to the All Party Parliamentary Group on Drones, Professor Stuart Russell, Professor of Electrical Engineering and Computer Sciences at the University of California, argued that an improvised small armed autonomous drone is something that a competent group could develop, which could then be fielded in large numbers within eighteen months to two years. "It's really not a basic research problem," he stated.[11]

However, the extent to which autonomous weapons will be able to distinguish between combatants and non-combatants and between friendly forces and enemies is open to question. Even highly advanced systems are unlikely to be able to judge whether destroying a potential target is a proportionate act and a military necessity, as required under the laws of war. Nevertheless, such systems may have the capability, for example, to locate and kill everyone within a defined geographical area in which a military commander have decided that only enemy combatants are to be found. Worryingly, autonomous weapons could potentially also be programmed to select targets on the basis of factors such as ethnicity, gender, age, and behaviour.

> Even highly advanced systems are unlikely to be able to judge whether destroying a potential target is a proportionate act and a military necessity

2.3 Intelligence Analysis

The impact of autonomy and the development of autonomous weapon systems will fundamentally affect how the wars of the future are fought. However, it is important to be aware that as well as increasing autonomy in weapons systems themselves, autonomy is having an equally important impact on other aspects of warfare, in particular the analysis of intelligence and target setting.

Modern warfare relies on vast quantities of electronic intelligence information from various sources. This includes signals intelligence intercepts, satellite images, and geolocation data, as well as video, photographic, radar, and other intelligence information. In his book 'Unmanned: Drones, Data, and the Illusion of Perfect Warfare', American security analyst William Arkin argues that drones are the visible element of a military 'data machine', which gathers, analyses and distributes vast amounts of intelligence, using it to select and destroy targets.[12] It is this aspect of warfighting that is growing, and is becoming increasingly automated. The US military, in particular, is now beginning to use its data to find new ways of gaining a military advantage by using artificial intelligence to help process vast quantities of information into usable intelligence. In the longer term, according to defence journalist Patrick Tucker, the US military aims to connect every asset on the global battlefield to become "an unimaginably large cephapoloidal nervous system armed with the world's most sophisticated weaponry … the purpose: better coordinated, faster, and more lethal operations in air, land, sea, space, and cyberspace."[13]

11 Evidence by Stuart Russell to All Party Parliamentary Group on Drones. 31 October 2017 – Transcript of Fourth Evidence Session. http://appgdrones.org.uk/31-october-2017-transcript-of-fourth-evidence-session/

12 William M. Arkin: 'Unmanned: Drones, Data, and the Illusion of Perfect Warfare'. Little, Brown, and Company 2015. P17-18.

13 Patrick Tucker: 'The Future the US Military is Constructing: a Giant Armed Nervous System'. Defense One, 26 September 2017. http://www.defenseone.com/technology/2017/09/future-us-military-constructing-giant-armed-nervous-system/141303

2.4 Models to enable discussion of autonomous weapon systems

Philosophers, politicians, scientists and lawyers continue to debate the concept of autonomy in machines and, in regard to autonomous weapon systems, various models have been proposed to enable discussion about whether there should be limits on developments and what those limits should be.[14] Here are some commonly used models:

The Loop model

The Loop model is based on how much human oversight there is in selecting and attacking targets.[15] According to this approach, weapons can be grouped into one of three categories:

- Human-in-the-Loop weapons: Weapon systems that can select targets and deliver force only with a human command.
- Human-on-the-Loop weapons: Weapon systems that can select targets and deliver force under the oversight of a human operator who can override the weapon's actions.
- Human-out-of-the-Loop weapons: Weapon systems that are capable of selecting targets and delivering force without any human input or interaction.

The Loop model focuses on autonomous military systems that have lethal capabilities and are able to select targets and deliver force. Although it is helpful in understanding levels of human control over a lethal autonomous weapons system and in discussing associated ethical and legal issues, it does not provide a framework to consider other aspects of autonomy in the 'kill chain' such as use of autonomy in intelligence analysis of potential targets, or in long-term ongoing surveillance systems.

The Spectrum model: level of human control and automation

Military systems can be grouped into four main sets depending on their level of control and automation:[16]

- Inert systems, which have no automated features of note.
- Remotely controlled systems, which are controlled directly by a human operator.
- Automated systems (sometimes also called semi-autonomous) which can act independently of external human control but only according to a set of programmed rules.
- Autonomous systems, which can act without human control and define their own actions, albeit within the broad constraints or bounds of their programming.

Under this model autonomy can be thought of as a spectrum (see Figure 1), depending on the degree of human control, extending from inert systems which require direct human operation, through to remote controlled, automated,

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14 International Committee of the Red Cross: 'Autonomous Weapon Systems: Technical, Military, Legal and Humanitarian Aspects'. 2014, op cit. P61-64.

15 Bonnie Docherty: 'Losing Humanity: The Case Against Killer Robots'. Human Rights Watch, 19 November 2012. https://www.hrw.org/report/2012/11/19/losing-humanity-case-against-killer-robots. The definition originally presented by Human Rights Watch used the term 'robots' instead of 'systems' but we have used the word 'system' to emphasise that automated weapons can take a wider variety of forms than the popular view of a robot.

16 International Committee of the Red Cross: 'Autonomous Weapon Systems: Technical, Military, Legal and Humanitarian Aspects', op cit. P62.

and finally to fully autonomous systems which can operate independently.[17] Autonomous weapon systems currently in operation are located in the lower to middle part of the spectrum (remotely controlled and automatic), but some states are actively undertaking research which would allow the development of fully autonomous lethal weapons.

Figure 1: A spectrum of autonomy

Decreasing human control →				
Inert system	**Remotely controlled system**	**Automated system**	**Autonomous system**	**Highly intelligent autonomous system**
SA80 assault rifle	Hellfire missile	Phalanx close-in weapon system	Taranis drone?	Yet to be designed

Classifying weapon systems in this way, according to the amount of autonomy they exhibit, is useful in understanding what a weapon is capable of, but it does not address legal or ethical considerations and there may not always be a clear line between 'automated' and 'autonomous' weapon systems.

Critical function model

Models based around 'levels' of autonomy may have limitations when considering weapon systems which incorporate autonomous operation for different functions.

Today's armed drones are often described as 'remotely controlled', but in reality many of their key functions are already automated or autonomous, for example in take-off and landing, navigation, and software updating. Many would consider these to be acceptable functions to automate, and there is much greater concern about weapons systems autonomously identifying and selecting targets, and even more so over them making decisions on when to use force and operate a weapon. It can therefore be helpful to focus on autonomy in the different functions of a weapons system, rather than autonomy in the overall system itself.[18] A key factor therefore would be the level of autonomy in functions required to select and attack targets (usually known as critical functions), such as target acquisition, tracking, selection, and fire control.

Figure 2: Functions involved in the control of a drone, showing 'critical functions.'

Green: non-critical function   **Amber:** may be critical in some situations
Red: critical function relating to the use of force

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17   United Nations Institute for Disarmament Research (UNIDIR): 'Framing Discussions on the Weaponization of Increasingly Autonomous Technologies'. 2014, op cit.

18   International Committee of the Red Cross: 'Autonomous Weapon Systems: Technical, Military, Legal and Humanitarian Aspects', op cit. P62.

While this model focuses on the most problematic aspects of autonomy in weapon systems, others argue that it could normalise the development of autonomy in weapon systems and allow them to be developed piecemeal.

Legal compliance model

Alongside technical-based models, legal questions should be asked to ascertain whether autonomous weapon systems are capable of complying with various aspects of international law. For example:

- What is the role of the weapon with autonomy?
- How much autonomy does the weapon system have in this role?
- What are the relevant legal issues?
- Does the weapon system have the capability to fulfil legal requirements?
- Are there capability gaps that prevent compliance with laws of armed conflict and policy requirements? Do they need humans to fill them, and/or place restrictions on autonomous weapon system behaviour in place? [19]

The UK's Ministry of Defence broadly adopts the spectrum model, arguing that it is important to distinguish clearly between automated and autonomous systems, and has published the following definitions in relation to drones:[20]

- *Automated system:* "In the unmanned aircraft context, an automated or automatic system is one that, in response to inputs from one or more sensors, is programmed to logically follow a predefined set of rules in order to provide an outcome. Knowing the set of rules under which it is operating means that its output is predictable."
- *Remote and automated system:* "A system comprising the platform, control and sensor equipment, the supporting network, information processing system and associated personnel where the platform may be operated remotely and/or have automated functionality."
- *Autonomous system:* "An autonomous system is capable of understanding higher-level intent and direction. From this understanding and its perception of its environment, such a system is able to take appropriate action to bring about a desired state. It is capable of deciding a course of action, from a number of alternatives, without depending on human oversight and control, although these may still be present. Although the overall activity of an autonomous unmanned aircraft will be predictable, individual actions may not be."

However, the Ministry of Defence's definition of an autonomous system is much narrower than those used by other governments and international institutions, partly in order to play down fears over the development of autonomous weapons. In essence, it argues that a machine is not truly autonomous unless it virtually has the equivalent capability of a human. With this definition in place, the MoD goes on to argue that "the UK does not possess fully autonomous weapon systems and has no intention of developing them. Such systems are not yet in existence and are not likely to be for many years, if at all."[21]

> The Ministry of Defence's definition of an autonomous system is much narrower than those used by other governments and international institutions

19 Joshua Hughes: 'What is autonomy in weapon systems, and how do we analyse it? An international law perspective'. In 'Autonomy in Future Military and Security Technologies: Implications for Law, Peace, and Conflict',. The Richardson Institute, Lancaster University, 10 November 2017. pp 33-44 https://ttac21.files.wordpress.com/2017/11/richardson-institute-autonomy-in-future-military-and-security-technologies-implications-for-law-peace-and-conflict.pdf . To add to Hughes' analysis, we would also advocate asking 'What are the capabilities of the weapon?'. This allows consideration of the consequences of its unlawful use, and the possibility that it might be used in ways which its designers had not foreseen or intended.

20 Ministry of Defence: Development, Concepts and Doctrine Centre: 'Unmanned Aircraft Systems'. Joint Doctrine Publication 030.2, 12 September 2017. P13-15. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/673940/doctrine_uk_uas_jdp_0_30_2.pdf

21 Ministry of Defence: Development, Concepts and Doctrine Centre: 'Unmanned Aircraft Systems', op cit. P15.

The definition of autonomous weapon systems that we use for the purpose of this report is the one which has been proposed by the International Committee of the Red Cross:

> "Any weapon system with autonomy in its critical functions. That is, a weapon system that can select (i.e. search for or detect, identify, track, select) and attack (i.e. use force against, neutralize, damage or destroy) targets without human intervention."[22]

This definition, and our report, draws largely on the critical function model to analyse the issue, as we believe the gradual evolution of autonomy in different functions of a drone is providing the 'building blocks' for development of truly autonomous lethal drones. However, we would emphasise that no one one of these models on their own is capable of giving a complete understanding of the concept of autonomy in weapon systems.

2.5 Drivers for the increased use of autonomous technology within drones

As well as the obvious factor that autonomous weapon systems allow one's own personnel to be removed from the risks of the combat zone, robotic systems do not feel fatigue or experience fear, unlike human soldiers. In addition, computers are able to process large quantities of certain types of data far quicker than humans and so autonomous weapon systems potentially have the ability to act much faster and much more accurately than humans, giving them a military advantage over human pilots and soldiers.

Advocates of autonomous weapon systems claim that better reaction times and speedier decision-making might allow autonomous systems to make higher quality, faster decisions than their human counterparts. They also suggest that improved accuracy enabled by autonomous systems may result in a reduction in the number of civilian casualties during warfare. On the other hand, uncertainty over the outcomes of using artificial intelligence to enable autonomous weapons to make decisions raises the risk of indiscriminate killing, resulting in greater numbers of civilian deaths. The introduction of autonomy into the critical functions of a weapons system certainly entails sacrificing invaluable human traits such as empathy, judgement, and compassion which are crucial if war is to be waged consistently with humanitarian laws.

The sensor pod on a Predator drone contains sophisticated cameras, radar, and electronic tracking equipment.
Credit Cohen Young, US Air Force

22   International Committee of the Red Cross: 'Views of the International Committee of the Red Cross (ICRC) on autonomous weapon systems'. Working paper prepared for the Convention on Certain Conventional Weapons Meeting of Experts on Lethal Autonomous Weapons Systems (LAWS),11-15 April 2016, Geneva. https://www.icrc.org/en/download/file/21606/ccw-autonomous-weapons-icrc-april-2016.pdf

Autonomous functions can also be expected to reduce the number of personnel needed to operate weapons systems, with corresponding reductions in financial costs. Personnel requirements will drop, for example, if a single commander or small team is able to control multiple unmanned systems. Already the US Air Force has developed a strategy to reduce piloting requirements for Reaper drones by using multi-aircraft control and automated features. In the longer term, more sophisticated unmanned systems might also be able to complement or substitute for the 'boots on the ground' role of traditional land forces, allowing a smaller number of troops to achieve a military objective. Unlike humans, of course, such weapon systems do not require ongoing pay, training. leave, pensions, or medical care, adding to the financial incentives for their use.

While being without a pilot on board gives drones certain advantages in combat, it also creates certain vulnerabilities, perhaps most importantly reliance on a communication link back to the pilot on the ground. If this link is broken, then the drone can no longer be operated and it becomes useless. Communications links to drones are vulnerable to interference through jamming aimed at blocking communication, 'spoofing' and hacking to disrupt control of the drone, and signals interception to obtain intelligence information.[23] By developing drones which can operate autonomously, using onboard computers instead of direct control from a human operator, these vulnerabilities can in theory be reduced. Advances in miniaturisation are now making this possible, although there is an inescapable trade-off between sensor and computing capacity and the size, weight, and power consumption requirements of a drone, which imposes limits on the potential for the automation of small drones.[24]

Onboard processing also reduces or eliminates the need for exporting large quantities of data from the drone, which would otherwise consume valuable bandwidth over a satellite link back to the ground control station. Away from the drone itself, increased processing power also has the potential to greatly expand the amount of information which is collected and used offline. The US Air Force has concluded that "most full motion video as well as imagery is used real-time but then 'falls on the floor' and is not optimally analysed to extract more knowledge of the enemy." In future it plans to use automated tasking, processing, analysis and dissemination methods to "meet real-time collection needs while providing a means to analyze a greater portion of the data/imagery collected."[25]

Finally, autonomous features would allow new military roles to be developed for drones. These could include new roles based around very long loiter times without human intervention, including surveillance roles where drones are able to generate a threat merely through their presence; operation in environments where communication is difficult or impossible, such as underwater or beyond the range of a transmitter; or in tracking missile launches as part of a ballistic missile defence network.[26]

23 David Hambling: 'Swarm Troopers: How small drones will conquer the world'. Archangel Ink, 2015. P264-5.

24 Darren Ansell: 'Research and Development of Autonomous 'Decision Making' Systems'. P40. In: 'Expert Meeting. Autonomous Weapon Systems: Technical, Military, Legal, and Humanitarian Aspects. Geneva, 26 to 28 March 2014'. International Committee of the Red Cross, November 2014. https://www.icrc.org/en/download/file/1707/4221-002-autonomous-weapons-systems-full-report.pdf

25 United States Air Force: 'Air Force Unmanned Aerial System (UAS) Flight Plan 2009-2047'. Headquarters US Air Force, 18 May 2009. Para 4.6.3.2, p49. https://fas.org/irp/program/collect/uas_2009.pdf'

26 Patrick Tucker: 'Drones Will Help Protect Guam From North Korean Missiles'. Defense One, 22 August 2017. http://www.defenseone.com/technology/2017/08/drones-will-help-protect-guam-north-korean-missiles/140400/

More significantly, the ability to locate and destroy targets without human intervention means that autonomous drones are what systems engineers call 'scalable' – one operator can command a very large, theoretically limitless number of systems. This means they could be used in completely different ways to current weapon systems. "Three million Kalashnikovs need three million soldiers to use them. If you want to launch three million autonomous weapons, you just need … $150 million and a couple of programmers to set up the mission definition, and that's it," argues Stuart Russell. Flooding an area with a large number of small lethal autonomous drones is a "real possibility in the not too distant future" and has the potential to kill "very large numbers of people," with the possibility of 'dialling in' the number and type of targets that the drones would be programmed to select.[27]

While such scenarios may seem a million miles away, the underlying research to develop such systems is already underway, and to which we now turn.

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27 Evidence by Stuart Russell to All Party Parliamentary Group on Drones, op cit.
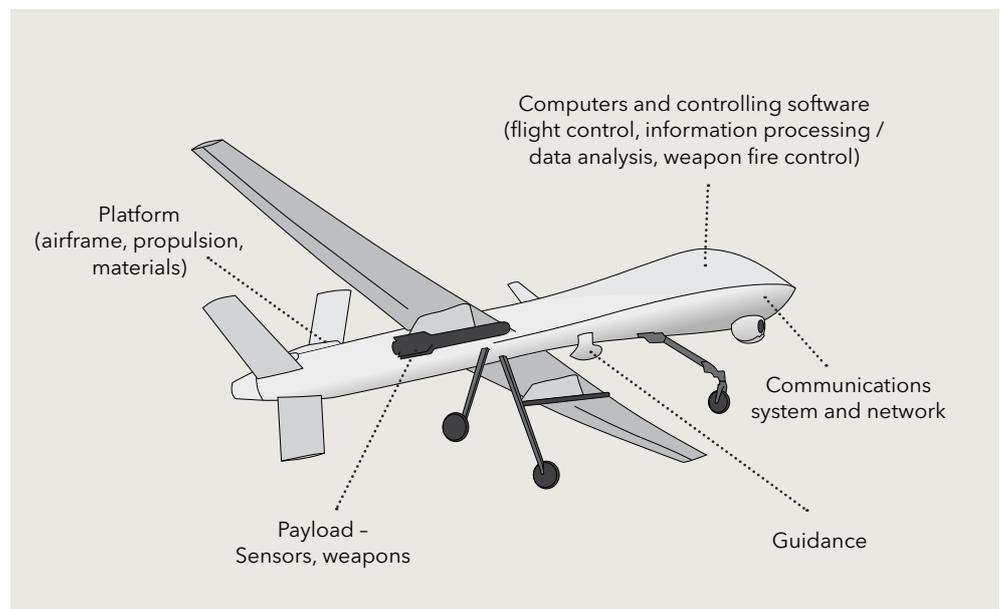
Building blocks for an autonomous armed drone

Increasingly autonomous drones are likely to emerge as new combinations of existing technologies rather than entirely new systems

Breaking it down

Drone technology is currently advancing in incremental steps as successive improvements in the individual key components – the platform, payload, control system, and the communications network – result in improved capability. Increasingly autonomous drones are likely to emerge as new combinations of existing technologies rather than entirely new systems. For example, a software upgrade could allow a remotely piloted drone to become capable of autonomous flight, an unarmed drone could be equipped with highly automated sub-munitions, or an armed drone could be equipped with multiple weapon systems. Drones are already increasing in autonomy and computational intelligence as successive versions of the same system emerge. The Predator drone, it should be remembered, evolved from a simple reconnaissance drone into a hunter-killer aircraft with sophisticated automated features over the course of thirty years.

Figure 3: Anatomy of a drone (adapted from Pratap Chatterjee and Christian Stork).[28]

Computers and controlling software
(flight control, information processing /
data analysis, weapon fire control)

Platform
(airframe, propulsion,
materials)

Communications
system and network

Payload –
Sensors, weapons

Guidance

28   Pratap Chatterjee and Christian Stork: 'Drone, Inc: Marketing the Illusion of Precision Killing'. Corpwatch, August 2017. http://www.corpwatch.org/article.php?id=16105

The extent to which increasing autonomy within a drone might raise concerns will depend upon the level of human control over 'critical functions,' the task assigned to the drone, the amount of planning for the task, and the capability of the system to discriminate targets.

Autonomous capabilities may be divided into those which are 'critical' (those involved in the targeting and launch of weapons) or 'non-critical' (those which do not relate to a decision to attack a target, but which may nevertheless be important in enabling a drone to perform a particular role). Non-critical capabilities could include functions such as flight, navigation, or loitering, while critical functions could include target recognition and the arming and firing of weapons (see below). As a simple example, use of an armed autonomous drone may be problematic, but use of a similar drone fitted with a video camera for intelligence gathering instead of a weapon might be considered acceptable.

Existing systems such as the Phalanx air defence weapons system are capable of operating with a degree of autonomy. Such weapons are able to detect and identify targets, and so arguably operate autonomously at the border of critical and non-critical functions. However, at present human intervention at specific points during their operation ensures that human control is maintained over the use of force,[29] and so they do not qualify as truly autonomous weapons. Another important factor is that they are single-task systems which operate only in simple and uncluttered environments where there is a low risk of them detecting civilian objects or friendly forces which may be mistaken for a target.

Table 1: Generic Categorization of autonomous features in military platforms and systems

General Capability area	Autonomous ability	Tasks
Mobility	Ability for the systems to govern and direct its motion within its environment	Navigation Take-off/landing Collision avoidance Follow me Return to base
Health management	Ability for the system to manage its functioning and survival	Fault detection Self-repair Power management
Interoperability	Ability for the system to collaborate with other machines or humans	Multi-agent communications and coordination (swarming) Human-machine interaction through natural language communication
Battlefield intelligence	Ability to collect and process data of tactical and strategic relevance	Data collection Data analysis
Use of force	Ability to search for, identify, track or select and attack targets	Target detection Target identification Target tracking Target selection Fire control

Source: SIPRI data set on autonomy in weapon systems. **Credit** Vincent Boulanin: 'Mapping the development of autonomy in weapon systems. A primer on autonomy'. Stockholm International Peace Research Institute. 2016

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29   International Committee of the Red Cross:'Expert Meeting. Autonomous Weapon Systems: Implications of Increasing Autonomy in the Critical Functions of Weapons', op cit. P14.

3.1 Autonomous functions

A significant proportion of the various functions of a weapon system can now operate autonomously and these have been categorised systematically by Vincent Boulanin for the Stockholm International Peace Research Institute (SIPRI).[30] Based on this framework (see Table 1 and Figure 3), we set out here which functions and tasks are important in enabling the development of an autonomous armed drone.

Mobility

Mobility relates to the functions that allow a drone to control and direct its own flight and motion. Key activities which an autonomous drone will need to be able to successfully undertake include:

Navigation and flight control: Autonomous flight and navigation can allow a drone to fly without the need to communicate with a ground control station, allowing it to operate independently, maintain its stealth, and avoid signal jamming. Computer-based autopilots are now able to fly commercial aircraft in many situations, and similar software can be developed to monitor and control the flight of a drone. Navigation software controls the flight path of the drone to a target area using an inertial navigation system and / or information from navigation satellites. The software reads the drone's current position and then controls a flight control system to plan and steer a course towards the destination, climbing, cruising, and descending as necessary. The system may also able to optimise the airspeed, avoid bad weather, and control flight stability against buffeting by wind.

Take off and landing: An autonomous drone must have the ability to take off and land using pre-programmed rules and find safe landing areas for emergency use.

Manoeuvring and collision avoidance: Drones of all sizes represent a significant collision hazard to other aircraft operating in the same airspace, and, in congested urban areas, are at risk of collision with obstacles and ground features. Sense and avoid technology, based on vision-based aircraft detection, radar, and autonomous flight control is necessary to avoid collisions. This is an essential feature for larger drones if they are to be permitted to fly in regulated and congested civil airspace.

Follow me: Programming which allows the drone to follow a human, other drones or vehicles, or to chase and home in on a potential target.

Persistence / loitering: The ability to linger in a particular area for some time, while, if necessary, searching for targets.

Return to base: Software allowing the drone to return home, for example in the event of a loss of communication.

Health management

Health management concerns functions that allow systems to manage and maintain their operation. Autonomous drones may need to undertake the following activities:

Fault detection: Faults can be detected and diagnosed by collecting and monitoring data from critical systems and regularly checking individual components.

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30   Vincent Boulanin: 'Mapping the development of autonomy in weapon systems. A primer on autonomy'. Stockholm International Peace Research Institute. 2016, op cit. P8.

Power management: When the drone detects that its power resources are low, it will need to automatically refuel or recharge itself, or switch certain components into standby mode.

Self maintenance / repair: Self repair functions require a drone to be able to make adjustments to itself and have access to spare parts – maybe at a base station. These capabilities are still at a conceptual stage.

Reconfiguration: In some situations it may be advantageous for a drone to be able to reconfigure itself to a new formation, for example by folding its wings, changing its geometry, or switching between fixed wing and rotary wing modes of operation.

Interoperability

Interoperability is the ability of a machine to undertake a task in collaboration with other machines (known as machine-machine teaming) or humans (human-machine teaming). Technology development in both areas is still at a very early stage.

Information sharing: Systems can be connected and can communicate with each other to share sensor, intelligence, and / or target information.

Machine-machine teaming technology may allow drones to 'self-organise' into swarms in the same way as birds and insects.
Credit John Holmes

Machine–machine teaming: Although there is much current research in this field, only simple experimental systems have so far been developed which are merely able to exchange data at a basic level. Swarming is an example of machine-machine teaming where software governing collective behaviour allows large numbers of small, low cost drones to 'self organise' and act in concert. Swarming has been successfully demonstrated in an experiment conducted in 2016 by the US Department of Defense's Strategic Capability Office together with the US Naval Air System Command using 103 Perdix micro-drones.[31] Swarming has been predicted to have a major impact on the future of warfare by enabling the co-ordinated collection of intelligence over a wide area, 'area denial' operations intended to prevent an enemy from occupying or using a certain area, and distributed attacks on a single point from multiple sources.

Human-machine teaming: In human-machine collaborations drones would work independently alongside humans to undertake a mission, for example by watching and protecting human troops and operating weapons when told to. The development of natural language communication, both through speech and gestures, is considered to be a key element in enabling human-machine teaming. As yet there are no known examples of human-machine teaming and the technology remains conceptual.

Situational analysis and dynamic planning

Drones operate in environments which are subject to continuous change, and autonomous drones will need to continually monitor and assess the surrounding environment in order to be able to adapt to changing circumstances.

Tactical planning: Autonomous drones will require software that will allow them to interpret a dynamic environment and formulate the best tactics and plan for responding to changes around them. The ability to rapidly update information databases in real time could allow a drone to decide on the timing of an attack on a target so as to gain the maximum military advantage.

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31 Erik Slavin: 'Pentagon unveils Perdix micro-drone swarm'. Stars and Stripes, 10 January 2017.
https://www.stripes.com/news/pentagon-unveils-perdix-micro-drone-swarm-1.448124

On-the-fly analysis of threats: Drones would need to have the ability to avoid rapidly emerging threats and take evasive action or respond otherwise. This would require the capacity to detect threats using radar or other sensors, and to discern between friendly forces and an incoming threat.

Self-protection: The ability to take defensive actions to evade or eliminate a threat, such as jamming electronic signals or using weaponry to destroy a threat.

Intelligence gathering

A key function of drones is to find, collect, and analyse intelligence – information that may be of strategic or tactical relevance. This information may be passed back to a command centre to assist decision making or processed on board and passed on to the drone's weapon systems. The functions which allow this to take place are as follows:

Data collection: The ability to track and identify objects and keep them under surveillance, using a range of sensor types. Full motion video (video footage of sufficient quality to make motion appear continuous to humans), synthetic aperture radar (a form of radar used to create two- or three-dimensional images of objects and landscapes), and thermal and infra-red imaging are currently commonly used sensors, but other techniques, such as electronic methods for identifying mobile phone signals, can also be employed.[32]

Data analysis: Software is required to discern the nature of objects located by the drone and establish which may be potential targets. At the moment the ability of onboard systems to sift and analyse data is rudimentary, but 'change detection' software is developing rapidly and advances in machine learning are expected to enable improvements in computer image recognition capabilities.

Communication of data to other network nodes: Data can be exported from the drone for use and interpretation alongside information from other sources, for detailed secondary analysis, and / or for archiving. Data can also be imported from elsewhere to assist in analysis and decision-making.

Use of force

Use of force is the most problematic of the functions that drones might be able to undertake autonomously. It relates to capabilities that allow weapon systems to hunt for, identify, and track enemy targets and then execute attacks on them. In terms of target detection and identification functions, there is a 'grey area' of overlap with some elements of intelligence gathering functions depending on the purpose for which information is used.

Target detection: As a first step towards the use of force, a drone must be able to find and track a target. The drone's sensors play the key role in this process by detecting radar, acoustic, visual, infra-red, or other electromagnetic signals and using them to allow the drone to locate objects.

Target recognition: Automatic target recognition is an established technology through which software is able to identify a potential target by analysing incoming sensor data and matching it to a pre-programmed library of signatures, allowing it to identify an object as a target. At present such software is only able to detect large targets or those with characteristic signatures, such as tanks, ships, missiles, or radar systems, in relatively simple, low-clutter

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32   For an analysis of drone sensor technology and processing software see Pratap Chatterjee and Christian Stork: 'Drone, Inc: Marketing the Illusion of Precision Killing'. 2017, op cit.

environments. Unlike humans, who are able to use multiple sensory inputs to interpret a situation and make a decision, drones are usually limited to two or three sensor inputs to provide information, and they cannot evaluate morally or legally whether a target should be attacked. There are significant obstacles to developing reliable automatic target recognition software further.

Target tracking identification, and prioritisation: Algorithms associated with target recognition software which allow targets to be tracked and decisions to be made on engaging with them.

Fire control: Software and systems to line up a target, decide on the timing of when to fire a weapon, arm the weapon, select the correct detonation timing and fusing settings, and execute the command to fire the weapon.

Decision on legality and proportionality: The use of weapon systems which are autonomous in their critical functions carries a risk that they might be used indiscriminately or against civilian targets, contrary to the laws of armed conflict. Any targeting decision must assess the proportionality of the action to be taken and ensure that the action complies with the law. Such decisions are highly complex and based on a wide range of subjective factors. It is difficult to see how computer systems will be able to take such decisions meaningfully in the foreseeable future.

3.2 Current capabilities of drone technologies

A broad range of weapon systems showing some degree of autonomy in their operation have been developed, although none, as yet, have the capability of making 'intelligent' targeting decisions. Researchers at Arizona State University have catalogued 273 weapon systems with some autonomous functions which have been deployed – the most primitive of which date back to the early 1960s – and a further ten which are currently under development.[33] Nineteen of the systems are described as unmanned aerial vehicles.

The Arizona State University study shows that the most common systems with some degree of autonomy are missile-based. Homing technology emerged as an early development and is the most frequently occurring dimension of autonomy among those tracked in the study. Homing technology is based on relatively simple techniques, such as radar and thermal imaging, which form the basis of more sophisticated autonomous functions such as target identification and target image discrimination.

Navigation is the second most frequently encountered autonomous characteristic, with a rapid expansion in use from 2000 onwards as a result of the development of GPS technology. Target acquisition and offensive target identification technologies were observed at a roughly similar frequency. Technology which allows weapons systems to positively identify and select a target emerged at a relatively early date in the development of autonomous systems, particularly for use in air-to-air missile systems where there was a need to accurately discriminate between friendly and hostile aircraft. Over the last ten years target image discrimination and loitering / self-engagement technologies have emerged and have been incorporated in weapon systems aided by improvements in computer vision and image processing.

A number of the weapon systems currently in service with the UK's armed forces are able to select targets automatically, showing some degree of autonomy. The Ministry of Defence was unable to provide us with a comprehensive list of

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33   Heather Roff and Richard Moyes: 'Project: Artificial Intelligence, Autonomous Weapons, and Meaningful Human Control'. Arizona State University, April 2016.

these weapons,[34] but Appendix I shows a number of such systems for illustrative purposes, giving an indication of what autonomous military technology is currently capable of achieving. Although the majority of these are missile-based systems, a broad range and variety of unmanned and automatic systems are used by the British military, encompassing between them, at some level, the various dimensions of autonomy. However, systems which can undertake the critical function of selecting targets autonomously, such as the Phalanx close-in weapon system, are currently defensive systems with limited capabilities. They are intended to fire autonomously in situations where the time of engagement is too short for humans to be able to respond, but nevertheless operating under overall human supervision.

Although advanced technology has enabled the automation of weapon systems in many areas, there are still significant limitations to what autonomous weapon systems and drones are currently able to achieve. Impressive capabilities have been shown in demonstrator systems, but that is not the same as an operational system. While these may perform well in trials, they may not be able to cope with complex environments, poor weather, or disruptive measures from an enemy. It is not yet possible to guarantee that an autonomous weapon system will be able to operate safely and reliably in complex, uncertain, or contested environments.

In the longer term it has been predicted that the degree of autonomy in weapon systems will increase dramatically, and that it will be possible to build weapons able to conduct to a greater or lesser extent all of the functions described above (section 3.1). The Ministry of Defence considers it inevitable that unmanned aircraft "will eventually have the ability to independently locate and attack mobile targets, with appropriate proportionality and discrimination, but probably not much before 2030."[35] This does not mean, though, that autonomous weapons will develop in a simple and straightforward way towards full autonomy, or even that this would necessarily be seen as a militarily desirable goal. Advances are more likely to be made in the development of the 'building block' components across the range of autonomous functions, with a trend towards supervised autonomy rather than completely unmanned systems.

While truly autonomous weapon systems do not yet exist, research is under way in the UK which would enable their development. The next part of the report examines such programmes in more detail.

> While truly autonomous weapon systems do not yet exist, research is under way in the UK which would enable their development

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34 Ministry of Defence Global Issues: Response to request for information 2017/08149, 30 November 2017. MoD does not hold a central list of such systems.

35 'The UK Approach to Unmanned Aircraft Systems'. Joint Doctrine Note 2/11. Ministry of Defence Development, Concepts and Doctrine Centre, 30 March 2011. Para 311, p3-6. https://www.gov.uk/government/publications/jdn-2-11-the-uk-approach-to-unmanned-aircraft-systems

Armed and autonomous: a survey of current British research and development

Who is leading the development of autonomous drones and weapons?

The key scientific and engineering disciplines which underpin the development of autonomous technology are computing and artificial intelligence, robotics and sensing, and control theory. Aerospace and weapons engineering expertise is also important to the development of an armed autonomous drone.

The US leads global investment and activity in the development of artificial intelligence technology in general, with China generally seen to be rapidly catching up[36] and the UK and other European nations lagging behind. The majority of the largest arms manufacturing countries have identified artificial intelligence and robotics as important research and development areas.[37] China, Russia, and the US are all building centres for the development of military artificial intelligence.[38]

Using open source information and Freedom of Information requests, we have surveyed what research and development is being undertaken in this area here in the UK. Our analysis represents just a 'peep behind the curtain' and there is likely to much more activity under way than we have captured. The following organisations, companies, and agencies are involved in undertaking research and development work into autonomous technology, artificial intelligence, and drones.

4.1 UK Government

The government's Industrial Strategy, published in November 2017, pledges to "put the UK at the forefront of the artificial intelligence and data revolution" and to make the UK "a global centre for artificial intelligence and data-driven

36   Louise Lucas and Richard Waters: 'China and US compete to dominate big data'. Financial Times, 1 May 2018. https://www.ft.com/content/e33a6994-447e-11e8-93cf-67ac3a6482fd

37   Vincent Boulanin and Maaike Verbruggen: 'Mapping the development of autonomy in weapon systems', op cit. P104.

38   Patrick Tucker: 'China, Russia, and the US Are All Building Centers for Military AI'. Defense One, 11 July 2018. https://www.defenseone.com/technology/2018/07/china-russia-and-us-are-all-building-centers-military-ai/149643

innovation."[39] The Industrial Strategy also emphasises the importance of robotics as a priority area for industry in the future.

Government funding for basic research into artificial intelligence is provided mainly by the Engineering and Physical Sciences Research Council (EPSRC). Artificial intelligence is a priority for EPSRC, which has a high-level objective to support the development of a 'digital economy' and enable the delivery of intelligent technologies and systems.[40] Closely linked to this is the robotics research area, which is intended to grow in future as a proportion of EPSRC's funding portfolio.[41]

Ministry of Defence

Autonomous technology and data science are seen as "key enablers"[42] by the MoD, presenting "potential game-changing opportunities".[43] A 2015 review of the MoD's science and technology capabilities identified nine core areas, of which three are relevant to the development of drones and autonomous technology: Autonomous and Conventional Platforms; Surveillance Reconnaissance, Sensors and Space; and Command, Control, Communications, Computers & Intelligence & Big Data Analytics.[44]

> Autonomous technology and data science are seen as "key enablers" by the MoD, presenting "potential game-changing opportunities"

The Ministry of Defence's Science and Technology Strategy, published in October 2017, aims to 'mainstream' science and technology into the MoD's work and in meeting the UK's defence and security needs. The Strategy identifies a number of scientific areas, including autonomy and machine learning, as having a critical role in the development of future defence capabilities.[45] The MoD's current Chief Scientific Adviser, appointed in 2017 and responsible for delivering the strategy, is Professor Hugh Durrant-Whyte, who is an expert in robotics and data science.[46]

As part of the 2015 Strategic Defence and Security Review, the Ministry of Defence announced a Defence Innovation Initiative, intended to exploit the UK's civil sector science and technology research base to develop new military capabilities and allow closer research and development collaboration with allies, particularly the USA.[47] One of the priorities identified for the initiative is to "make better use of big data to inform timely and effective decision-making". A new 'Defence and Security Accelerator' programme, managed by the Defence Science and Technology Laboratory, has been formed to organise a series of Innovation Fund challenges, the first of which is to revolutionise the human information relationship for Defence.

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39 HM Government: 'Industrial Strategy – Building a Britain fit for the future'. 27 November 2017. P10, p38. https://www.gov.uk/government/publications/industrial-strategy-building-a-britain-fit-for-the-future

40 'Digital Economy'. Engineering and Physical Sciences Research Council website. https://www.epsrc.ac.uk/research/ourportfolio/themes/digitaleconomy/

41 'Robotics'. Engineering and Physical Sciences Research Council website. https://www.epsrc.ac.uk/research/ourportfolio/researchareas/robotics/

42 'Science and Technology Strategy 2017'. Ministry of Defence. 30 October 2017. Para 50, p21. https://www.gov.uk/government/publications/mod-science-and-technology-strategy-2017

43 'Corporate Plan 2017-2022'. Defence Science and Technology Laboratory. 21 July 2017. P4. https://www.gov.uk/government/publications/dstl-corporate-plan-2017-2022

44 'Supplementary Information to Science Capability Review Panel RAG Assessment (Summary)'. Ministry of Defence. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/458630/20150427-Supplementary_Information_Science_Capability_Review.pdf

45 'Science and Technology Strategy 2017'. Ministry of Defence, op cit. P15.

46 'MOD Chief Scientific Adviser Professor Hugh-Durrant-Whyte'. Ministry of Defence website, https://www.gov.uk/government/people/hugh-durrant-whyte

47 Mark Lane: 'Defence Innovation Fund set to unearth defence and security pioneers'. Defence Contracts Online website. https://www.contracts.mod.uk/do-features-and-articles/defence-innovation-fund-set-to-unearth-defence-and-security-pioneers/
"Advantage through Innovation: The Defence Innovation Initiative". Ministry of Defence, 16 September 2016. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/553429/MOD_SB_Innovation_Initiative_Brochure_v21_web.pdf

The Defence Science and Technology Laboratory (DSTL) has funded research into autonomous systems, sensing technology, and artificial intelligence.
Credit Crown Copyright

Defence and Science Technology Laboratory (DSTL)

The Defence Science and Technology Laboratory (DSTL) is an executive agency of the Ministry of Defence which is responsible for "delivering MoD's Science and Technology Programme using industrial, academic and Government resources".[48] DSTL is able to support targeted research which neither academia nor the private sector would be willing to conduct alone.

An insight into DSTL's interest in autonomous and unmanned technologies can be gained from looking at some of the programmes and projects it has supported in this field. DSTL's research portfolio, with 24 programme areas, includes programmes on Air Systems, Autonomy, Future Sensing and Situational Awareness, and Information Systems.[49]

DSTL spent approximately £14.4 million on work on unmanned air systems in 2015-16, of which 77% was spent externally on contracted work. This included funding to a consortium led by QinetiQ and including BAE Systems and Thales to deliver an "unmanned aircraft systems autonomy and mission management" contract. Funding was also awarded to a BAE Systems-led consortium of suppliers in an Autonomous Systems Underpinning Research (ASUR) programme to support DSTL in the delivery of underpinning technologies for unmanned systems[50] (see Case Study 1). Over the same period DSTL spent approximately £25.2 million on developing sensor technology, with the aim of integrating sensing capabilities for a variety of platforms (not just drones) to develop multi-function and networked sensing.[51] DSTL's programmes also aim to develop future technologies which will help to address size, weight and power limitations that govern the nature of sensor payloads for drones.[52]

Within the Command, Control, Communications, Computers & Intelligence (C4I) & Big Data Analytics area DSTL has funded 20 projects, several of which are being undertaken with support from a variety of industrial and academic partners.[53] These include projects on applied information processing, which aim to develop and implement imagery and geospatial standards and tools, and large-scale data, which aims to understand the benefits of big data technologies to MoD problems. QinetiQ and BAE Systems are contracted to undertake work on eight and seven of these projects respectively, and 14 universities have also been awarded contracts (see Appendix II).

DSTL is currently recruiting heavily in the data science field,[54] and the laboratory's in-house work on artificial intelligence and machine learning is believed to be exploring issues around working with sparse data sets, the levels of trust that can be invested in artificial intelligence systems, and working in coalition to develop artificial intelligence, as well as on opportunities for

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48 'Defence Science and Technology Laboratory Overview'. Defence Science and Technology Laboratory, 8 September 2017. https://www.gov.uk/government/publications/defence-science-and-technology-laboratory-overview

49 'Defence Science and Technology Laboratory Overview'. Defence Science and Technology Laboratory, op cit.

50 'Unmanned Air Systems'. Defence Science and Technology Laboratory. 1 July 2014. https://www.gov.uk/government/publications/unmanned-aircraft-systems-programme

51 'Integrated Sensing'. Defence Science and Technology Laboratory. 1 July 2014. https://www.gov.uk/government/publications/integrated-sensing-programme

52 'Remote Control: Remotely Piloted Air Systems – current and future UK use: Government Response to the Committee's Tenth Report of Session 2013-14'. House of Commons Defence Committee,: Sixth Special Report of Session 2014-15, 22 July 2014. Para 13, p10. http://www.publications.parliament.uk/pa/cm201415/cmselect/cmdfence/581/581.pdf

53 Response to Request for Information FOI 2017/10715. Ministry of Defence, 27 November 2017. https://www.whatdotheyknow.com/request/424240/response/1075872/attach/3/FOI%202017%2010715.pdf

54 'Do you want to be a Data Scientist at Dstl?' DSTL website article, 2 November 2017. https://www.gov.uk/government/news/do-you-want-to-be-a-data-scientist-at-dstl

using artificial intelligence technology to develop equipment for rapid use by the military to meet combat needs.[55] DSTL has also organised a number of crowd-sourcing competitions to take advantage of artificial intelligence and machine learning expertise among start-up companies, recent graduates and others working in computer science. The first of these was a Kaggle competition in which entrants were challenged to develop software to automatically detect and identify objects such as cars, trees, and buildings in a variety of environments from satellite images. The resulting software will be used in projects to analyse data and improve the UK's satellite intelligence gathering and analysis capability.[56] In November 2017 DSTL organised an 'artificial intelligence hackathon' under the auspices of its Defence and Security Accelerator scheme. The event was a two-day competition in which teams from the defence sector, industry, and academia were invited to use artificial intelligence techniques – "ranging from robotic process automation, neural networks, machine learning, deep learning and everything in between" – to solve defence management, information support, training and future workforce challenges. The winners were invited to submit a proposal for developing their ideas further.[57]

DSTL is also heavily involved in the MoD's work to develop the use of unmanned systems for use in the maritime environment[58] (a number of which were tested and highlighted as part of 'Unmanned Warrior' – a special part of the 'Joint Warrior' naval exercise in 2016). DSTL has also developed the Maritime Autonomy Surface Testbed (MAST) unmanned surface vessel, a speedboat which can be operated with various levels of autonomy from basic remote control up to fully autonomous navigation.[59] The laboratory has also developed various robotic land vehicles.[60]

Case Study 1 │ ASUR: Mapping the way towards autonomous armed drones

The Autonomous Systems Underpinning Research (ASUR) programme was a DSTL initiative which commenced in 2013 with the aim of developing an underpinning science and technology base to enable the production of intelligent unmanned systems for the UK's armed forces.[61] The programme was led by BAE Systems and brought together a consortium of potential future suppliers, including small and medium enterprises and academia as well as established military contractors.

The ASUR programme had a range of technical outputs, including sub-projects with the following titles:

55   Information from DSTL informant, 8 November 2017.

56   'Dstl's Kaggle competition has been a great success'. DSTL press release, 15 March 2017. https://www.gov.uk/government/news/dstls-kaggle-competition-has-been-a-great-success

57   'MoD Artificial Intelligence Hackathon' Tech UK. http://www.techuk.org/events/opportunity/item/11510-mod-artificial-intelligence-hackathon

58   Nick Hopkins: 'Ministry of Defence plans new wave of unmanned marine drones'. Guardian, 2 August 2012. https://www.theguardian.com/world/2012/aug/02/ministry-defence-plans-unmanned-marine-drones

59   'MAST goes into action at Unmanned Warrior'. Defence Science and Technology Laboratory press release, 20 October 2016. https://www.gov.uk/government/news/mast-goes-into-action-at-unmanned-warrior

60   'US and UK Armies lead the way in world first for robotic vehicles'. Defence Science and Technology Laboratory, 15 November 2017. https://www.gov.uk/government/news/us-and-uk-armies-lead-the-way-in-world-first-for-robotic-vehicles

61   Phil Williams: 'The Future for Unmanned Aerial Vehicles – Strategic Insights'. Presentation to Special Interest Group – Robotics and Autonomous Systems, 17 July 2014. Qi3. http://www.qi3.co.uk/wp-content/uploads/2014/07/Phil-Williams-Presentation-The-future-for-Unmanned-Aerial-Vehicles-UAVs-Strategic-Insights21.pdf

- From Data Gathering, through Mission Planning to Execution.
- Cooperative Surveillance Planning for Multiple Autonomous UAVs.
- Autonomous Swarm-Based Mission Planning and Management Systems.
- Feasibility Study of the use of a "Mixed Reality", Low Infrastructure C2 Environment for UAS Ground Stations.
- Multi-UxV – Global Planner for Navigation and Communications.
- Multi-objective Optimal Motion Planning and Formation Control of UAVs in Complex Urban Environments.
- Real-Time Adaptive Software Define Datalink Network Management.
- Maintaining Network Connectivity and Performance Using Multi-layer ISR System.
- Bio-inspired Robust Distributed Heterogeneous Sensor Management.

Among the research undertaken were projects aimed at developing sophisticated machine-machine teaming systems, swarm technology, and biomimetic drones controlled by machine learning applications.

- The 'Enhanced Awareness and Forward Operating Capability for Unmanned Air Systems (EA FOCUS)' project was undertaken by drone development company Blue Bear Systems Research and machine perception specialists Deep Vision Inc to develop machine-machine teaming technology, notably the ability to 'hand over' targets between multi layered autonomous systems. The research aimed to allow a higher-level drone to identify a target and hand over the target to a lower-level drone, such as a nano-drone, to allow tracking and covert operations. The architecture is reported to be scalable and transferable to in-service drones.[62]

- A project investigating 'Autonomous Swarm-Based Mission Planning and Management Systems' aimed to develop a swarm-based mission management and mission planning system capable of handling multiple fleets of drones involved in multiple missions simultaneously. Although the system was intended to be scalable, the demonstrator version was designed to allow one operator to govern four missions simultaneously with assistance from a 'virtual intelligent operator' – an on-screen avatar able to detect and flag up unforeseen situations and propose solutions.[63]

- A drone developed by the University of Bristol and BMT Defence Services which is capable of performing a perched landing. The drone is able to land in a small or confined space through use of 'morphing wing' engineering inspired by the wings of birds and controlled by machine learning algorithms.[64]

Defence and Security Accelerator

The Defence and Security Accelerator (DASA) scheme, part of the Defence Innovation Initiative managed by DSTL, aims to harness innovative ideas for the defence and security sector through themed competitions and an 'open call' for innovative projects. A number of recent DASA projects have been themed around unmanned technology and information analysis.

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62 'Deep Vision and Blue Bear Partner on ASUR Project'. Deep Vision Inc website article. http://www.deepvision.ca/asur-bb

63 'The ASUR Programme' webpage. Cached at https://webcache.googleusercontent.com/search?q=cache:Oe0YnXMDLyMJ:https://www.asur-programme.co.uk/category/projects/september-2014-call-challenge-1-unmanned-sensor-multi-layer-control-optimisation-and-exploitation/+&cd=2&hl=en&ct=clnk&gl=uk and accessed on 13 December 2017 but no longer online.

64 'BMT Develops First Ever UAV to Perform a Perched Landing Using Machine Learning Algorithms'. BMT Group news release, 4 January 2017. https://www.bmt.org/news/2017/01/bmt-develops-first-ever-uav-to-perform-a-perched-landing-using-machine-learning-algorithms/

A major DASA programme to revolutionise the human information relationship for Defence seeks to address the challenge posed by the growing amount of data accumulated by the military. It acknowledges that under current processes operators are unable to analyse and use information fast enough to make informed and effective decisions, and that in future even more sensor platforms will provide ever more data to the network. The competition aimed to develop new technologies, processes and ways of working to analyse and exploit data and "improve Defence's ability to operate and fight in the information age." The programme set three challenges for entrants:

- to devise ways to free up personnel through the use of machine learning algorithms and artificial intelligence;
- to allow for the rapid and automated integration of new sensors; and
- to improve operator cognitive capacity and greater human machine teaming.

Up to £6 million was available for the first two phases of the fifteen-month programme, with the prospect of securing further long-term funding from the Defence Innovation Fund.[65] The programme has led to the development of a new artificial intelligence decision making system that can provide intelligence analysts with cues to potential areas of interest or anomalies,[66] and help predict future events. The system is currently undergoing field testing with Joint Forces Command (see Case Study 2).

DASA's January 2017 'Beyond Battery Power' competition sought proposals for small, lightweight, modular technology to generate power for moving and sensing by portable robotic and autonomous systems.[67] The project aimed to develop power systems with an endurance of days, rather than minutes, and have a high energy density (greater than 1,000 watt hours per kg). In addition, they were expected to be reliable and to have a low acoustic and infra-red signature. A total of £1.5 million was available for the two phases of the eighteen month project.

The DASA scheme and its forerunner, the Centre for Defence Enterprise, have funded earlier programmes which can be expected to generate knowledge and technology relevant to the development of autonomous drones. These include the following programmes:

- 'Autonomy and big data for defence': Research into how automation and machine intelligence can analyse data to enhance decision making in the defence and security sectors.[68]
- 'Many drones make light work': Research into drone swarm technology aimed at designing modular drone platforms using common open systems architectures, demonstrating how a single operator could manage and command a swarm in excess of 20 drones, and understanding how swarm technology could help in developing new roles for drones.[69]

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65 'Competition document: revolutionise the human information relationship for Defence'. Defence and Security Accelerator. 10 August 2017. https://www.gov.uk/government/publications/accelerator-themed-competition-revolutionise-the-human-information-relationship-for-defence/competition-document-revolutionise-the-human-information-relationship-for-defence

66 'Intelligence technology to keep Joint Forces Command one step ahead of adversaries'. Ministry of Defence news story, 17 July 2018. https://www.gov.uk/government/news/intelligence-technology-to-keep-joint-force-command-one-step-ahead-of-adversaries

67 'Competition summary: beyond battery power'. Defence and Security Accelerator, 4 January 2017. https://www.gov.uk/government/publications/accelerator-themed-competition-beyond-battery-power/competition-summary-beyond-battery-power

68 '£100,000 for research into Automation and Machine Intelligence'. Defence Science and Technology Laboratory, 7 December 2016. https://www.gov.uk/government/news/100000-for-research-into-automation-and-machine-intelligence

69 'Competition document: many drones make light work'. Centre for Defence Enterprise, 25 October 2016. https://www.gov.uk/government/publications/cde-themed-competition-many-drones-make-light-work

- 'Persistent surveillance from the air': Research into sensor and communications technologies and communications networks to enable persistent surveillance operations from the air.[70]

- 'Seeing through the clouds': aimed at developing high resolution imaging techniques for use in poor weather conditions.[71]

- 'Autonomous last mile resupply': developing unmanned and autonomous technologies to allow delivery of supplies to forward combat locations.[72]

- 'What's inside that building?': to use new sensing technologies and approaches and new applications for traditional sensing methods to remotely assess what is inside a building.[73]

- An 'Enduring Competition' open call theme which has funded research into situational awareness and data analysis.[74]

4.2 Private sector – civil

Military planners are aware of the civil sector's lead in developing artificial intelligence and autonomous systems and are keen to have a slice of the cake

Investment and innovation in artificial intelligence is being led by the private sector, and not by the world's militaries. "The entire [US] government spent $1.1 billion on unclassified AI programs in 2015. The estimate for 2016 was $1.2 billion," according to Charlie Greenbacker, technical product leader at In-Q-Tel, a US venture capital firm which invests in high tech companies solely to allow them to support the US government's intelligence agencies. "Meanwhile, Softbank [a Japanese multinational conglomerate] has a $100-billion-dollar fund for this."[75]

The leading American internet companies – such as Alphabet (Google), which has been involved in the controversial Project Maven (Case Study 2), Microsoft, Amazon, Facebook, and Apple – have the data, resources, and technical expertise necessary to undertake the research and development needed to produce new software and pioneer intelligent autonomous products.[76] This research is often done in collaboration with leading universities and through the acquisition of smaller specialist companies. The automobile sector is another important area where data, resources, and technical expertise are plentiful and the development of autonomous technology is being driven forward. Major manufacturers such as General Motors, Volkswagen, and Ford are working on the development of driverless cars, in competition with newcomers such as Tesla, Waymo and Uber.[77] In the business sector artificial intelligence is emerging as an important factor in data-rich environments such as the retail and banking sectors.

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70 'Competition document: Persistent surveillance from the air'. Centre for Defence Enterprise, 12 June 2015. https://www.gov.uk/government/publications/cde-themed-competition-persistent-surveillance-from-the-air

71 'Competition document: seeing through the clouds'. Centre for Defence Enterprise, 26 May 2016. https://www.gov.uk/government/publications/cde-themed-competition-seeing-through-the-clouds/competition-document-seeing-through-the-clouds

72 'Competition document: autonomous last mile resupply'. Defence Science and Technology Laboratory, 29 June 2017. https://www.gov.uk/government/publications/accelerator-competition-autonomous-last-mile-supply/accelerator-competition-autonomous-last-mile-resupply

73 'Competition document: what's inside that building?' Centre for Defence enterprise, 10 September 2015. https://www.gov.uk/government/publications/cde-themed-competiton-whats-inside-that-building/competition-document-whats-inside-that-building

74 'Transparency data: Accelerator funded contracts: 1 April 2016 to 31 March 2017'. Defence Science and Technology Laboratory, 14 September 2017. https://www.gov.uk/government/publications/accelerator-funded-contracts/accelerator-funded-contracts-1-april-2016-to-31-march-2017

75 Patrick Tucker: 'China and the CIA are Competing to Fund Silicon Valley's AI Startups'. Defence One, 13 November 2017. http://www.defenseone.com/technology/2017/11/china-and-cia-are-competing-fund-silicon-valleys-ai-startups/142508

76 Christina Mercer: '11 tech giants investing in artificial intelligence'. Techworld, 27 November 2017. https://www.techworld.com/picture-gallery/data/tech-giants-investing-in-artificial-intelligence-3629737/

77 Michael Wade: 'Silicon Valley is winning the race to build the first driverless cars'. The Conversation, 22 February 2018. http://theconversation.com/silicon-valley-is-winning-the-race-to-build-the-first-driverless-cars-91949

Driverless cars are spurring the development of autonomous technology in the civil sector. **Credit** John K. Thorne / Flickr

Military planners are aware of the civil sector's lead in developing artificial intelligence and autonomous systems and are keen to have a slice of the cake. "The days of the military leading scientific and technological research and development have gone. The private sector is innovating at a blistering pace and it is important that we can look at developing trends and determine how they can be applied to defence and security" said General Sir Chris Deverell, Commander of Joint Forces Command, speaking at a NATO-organised conference aimed at developing links between the armed forces and the private sector. "In particular, and entirely consistent with the future force concept, I believe we need to look at the disciplines of artificial intelligence and machine learning, autonomy (including man/machine teaming), data analytics and visualisation, behavioural sciences, and simulation and modelling, that are now having a huge impact in the civil sector, but on which, I think, most defence departments lag behind."[78]

In order to capitalise on civil sector innovation, the Ministry of Defence set up the Defence Innovation Initiative in September 2016. Launching it, the then Defence Secretary Michael Fallon explained: "We're not just looking for traditional defence companies here. Numerous inventions from GPS and the World Wide Web to splash-proof technology have started life in the military. I want to reverse that as more non-defence companies bring their know-how to military matters. We get to use their niche capabilities, advanced business models, and different take on life. They get to realise the commercial benefit."[79] Dual use autonomous technologies, originating in the civil sector but adapted for military applications, are likely to become key components of the autonomous drones and weapons of the future.

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78 'International Concept Development and Experimentation conference 2017'. Ministry of Defence press release, 11 October 2017. https://www.gov.uk/government/speeches/international-concept-development-and-experimentation-conference-2017

79 Mark Lane: 'Defence Innovation Fund set to unearth defence and security pioneers', op cit.

"To them that data is…oil," argues William Roper, who runs the Pentagon's Strategic Capabilities Office. "It's wealth and fuel. Your data keeps working for you. You stockpile the most data that you can and train that to teach and train autonomous systems."

Case Study 2 How US and UK forces are beginning to use AI to support combat operations

Every day military aircraft, satellites and electronic sensors collect a colossal amount of intelligence information from around the globe – more raw data than the Department of Defence could analyse even if its entire workforce spent their whole lives at the task. The video sensors on a Reaper drone, for example, produce many terabytes of data every day and teams of analysts, even working 24 hours a day, are only able to exploit a fraction of the drone's sensor data. As a result, most of such surveillance data is archived without being looked at.[80] Now the military on both sides of the Atlantic are beginning to use big data resources in the same way as commercial companies like Facebook and Google. "To them that data is…oil," argues William Roper, who runs the Pentagon's Strategic Capabilities Office. "It's wealth and fuel. Your data keeps working for you. You stockpile the most data that you can and train that to teach and train autonomous systems."[81]

US: Project Maven

The Pentagon has now begun using artificial intelligence to help US armed forces process this 'avalanche of information' into valuable and usable intelligence. By using sophisticated machine learning processes to train a computer to recognise patterns and identify features in an image, much of the repetitive, low-grade work of information analysis – sorting, labelling, and describing objects – can be eliminated, allowing human analysts to focus on making decisions using the incoming material.

In April 2017, US Deputy Defense Secretary Bob Work set up Project Maven – formally known as the Algorithmic Warfare Cross-Functional Team (AWCFT) – to accelerate the integration of big data and machine learning by US armed forces, with the objective of turning the enormous volume of data available into actionable intelligence and insights at speed. The first task set by Work for the project team was to rapidly develop and field technology to automate the processing, exploitation, and dissemination (PED) of data from tactical-scale drones and full motion video from Predator and Reaper systems in support of US military operations in Iraq and Syria.[82]

Less than eight months later, algorithms developed by Project Maven were helping intelligence analysts exploit drone video over the battlefield. Computers using these algorithms were assisting intelligence analysts in identifying objects in video feed from ScanEagle drones used by US special operations forces. Before the technology could be deployed, the algorithms had to be 'trained' using thousands of hours of archived battlefield video captured by drones in the Middle East. A huge data set is required for this task, using data categorised and labelled in advance by humans. Training data needs to cover the full range of possible operating conditions, including different altitudes, object density, image resolution, and view angles. More than 150,000 images were used to establish the first Project Maven training data sets and it was anticipated that by the end of January 2018 the data set would

80   Gregory C. Allen: 'Project Maven brings AI to the fight against ISIS'. Bulletin of the Atomic Scientists, 21 December 2017. https://thebulletin.org/project-maven-brings-ai-fight-against-isis11374

81   Patrick Tucker: 'The Next Big War Will Turn on AI, Says US Secret-Weapons Czar'. Defense One, 28 March 2017. http://www.defenseone.com/technology/2017/03/next-big-war-will-turn-ai-says-pentagons-secret-weapons-czar/136537/

82   'Establishment of an Algorithmic Warfare Cross-Functional Team (Project Maven)'. Memorandum from the Deputy Secretary of Defense, US Department of Defense. 26 April 2017. https://www.govexec.com/media/gbc/docs/pdfs_edit/establishment_of_the_awcft_project_maven.pdf

include one million images.[83] Once labelled data is available, the algorithmic training process makes highly intensive demands on computers, and Project Maven had to build its own processing infrastructure, including computing clusters for graphics processing, from scratch.

When real-world deployment trials commenced the system was said to be able to identify objects such as people, vehicles, and different types of building correctly around 60% of the time, but after a week's 'on the job' learning and upgrades to refine the algorithms, the accuracy increased to around 80%. Further learning, as a result of analysts correcting mischaracterisations made by the system, is expected to increase accuracy still more.[84]

The Maven object identification algorithms are based on commercial technology – including open source image recognition software developed by Google[85] – which has allowed the project to move forward rapidly (Google subsequently withdrew from Project Maven following concerns among employees about the direction of the project).[86] The project team has combined these with a geolocation software system used by the US Navy and Marine Corps known as Minotaur. At the same time as the Maven software is able to display boxes on a video screen to classify and track objects of interest, Minotaur allows their locations to be displayed on a map.

If work proceeds to plan, Project Maven's algorithms will have begun to automate the analysis of video feeds coming from medium-altitude Predator and Reaper drones by the summer of 2018, and will then be applied to the 'Gorgon Stare' / ARGUS-IS camera system which allows Reaper to view an entire town. Although the algorithms currently function in the ground-based computers used to process intelligence data, a future goal is to programme them into onboard computers on the drones themselves – a significant milestone along the way to giving a drone the ability to identify potential targets itself.

Lieutenant General Jack Shanahan, director of the Project Maven team, believes that in future algorithms will be developed further to analyse information from other types of sensor platforms and intelligence data, including radar, signals intelligence, and even digital documents and open sources such as social media. Future roles for the technology might include war gaming, modelling and simulations, and providing early indications and warnings. "I expect a year from now, we'll see sensor operators and analysts using it in a way that we never understood was possible," Shanahan said.[87]

At the inception of Project Maven, the Defense Department was advised by experts in the artificial intelligence field to start by working on a narrowly defined, data-intensive problem where human lives would not be at risk and occasional failures would not be catastrophic – one reason why the project

83 Gregory C. Allen: 'Project Maven brings AI to the fight against ISIS'. Bulletin of the Atomic Scientists, op cit.

84 Marcus Weisgerber: 'The Pentagon's New Artificial Intelligence Is Already Hunting Terrorists'. Defense One, 21 December 2017. http://www.defenseone.com/technology/2017/12/pentagons-new-artificial-intelligence-already-hunting-terrorists/144742/

85 Kate Conger and Dell Cameron: 'Google Is Helping the Pentagon Build AI for Drones'. Gizmodo, 6 March 2018. https://gizmodo.com/google-is-helping-the-pentagon-build-ai-for-drones-1823464533?rev=1520349331358

86 Daisuke Wakabayashi and Scott Shane: 'Google Will Not Renew Pentagon Contract That Upset Employees'. New York Times, 1 June 2018. https://www.nytimes.com/2018/06/01/technology/google-pentagon-project-maven.html

87 Marcus Weisgerber: 'The Pentagon's New Artificial Intelligence Is Already Hunting Terrorists'. Defense One, op cit. Adin Dobkin: 'DOD Maven AI project develops first algorithms, starts testing'. Defense Systems, 3 November 2017. https://defensesystems.com/articles/2017/11/03/maven-dod.aspx

has focused on the analysis of video feed data as a test case for developing the technology. This means that, so far, some of the more difficult ethical and oversight challenges associated with the automation of warfare have been side-stepped. In due course, however – if computer analysis of intelligence data can eventually be used to determine whether an individual is directly engaging in hostilities and is thereby potentially subject to attack – avoiding the ethical and legal issues underpinning this technology will become impossible.

UK: Predictive cognitive control system at RAF Wyton

Following in the footsteps of the US military, the UK's Ministry of Defence is also working on military applications of artificial intelligence, albeit on a less extensive scale than Project Maven.

The Defence and Security Accelerator programme has led to the development of a new artificial intelligence decision making system that can provide intelligence analysts with cues to potential areas of interest or anomalies, and help predict future events.[88]

The Defence Intelligence Fusion Group is based in the 'Pathfinder' building at RAF Wyton. **Credit** Crown Copyright

Although full details of the system have not been published, the 'predictive cognitive control system' takes huge quantities of highly complex data, beyond the ability of analysts to comprehend, and uses deep learning neural networks to make confidence-based predictions of future events and outcomes which will be of "direct operational relevance" to the armed forces. It is able to automatically analyse data from multiple streams simultaneously and operates continuously in real time – all day, every day. The system has now reached the 'Beta' stage of its development and has been deployed in live operations at the Joint Forces Intelligence Centre at RAF Wyton, where it is being tested and refined in a realistic environment.

The system is being developed by technology company Montvieux Ltd, which provides "internet-facing systems"[89] and has also developed machine learning and data visualisation techniques for real time analysis of social media and other data[90] in partnership with the Centre of Intelligence Innovation.

88 'Intelligence technology to keep Joint Forces Command one step ahead of adversaries'. Ministry of Defence news story, 17 July 2018 https://www.gov.uk/government/news/intelligence-technology-to-keep-joint-force-command-one-step-ahead-of-adversaries

89 Digital Marketplace supplier: Montvieux. Gov.uk Digital Marketplace. https://www.digitalmarketplace.service.gov.uk/g-cloud/supplier/586042

90 'Montvieux Machine Intelligence – OSINT'. Gov.uk Digital Marketplace. https://www.digitalmarketplace.service.gov.uk/g-cloud/services/641838084246034

> Although Montvieux did not respond to our enquiries, the system is based on "all source text analysis,"[91] and we conjecture that its features may allow real-time analysis of information from Facebook, Twitter, and similar feeds from across the internet, among other sources.

4.3 Private sector – military

Not surprisingly, private sector military contractors are heavily engaged in research into autonomous systems and drones. Although the military technology research sector is smaller than the civil technology research sector and has fewer resources, it is in a position to adapt existing military systems and is adept at anticipating military needs and pursuing military contracts. As with government-funded research, projects are often taken forward through a consortium involving various industrial and academic partners, with the aim of combining expertise in different areas to produce a marketable product.

All the major international military contractors are involved in the development of autonomous systems and drones. Lockheed Martin, Boeing, Airbus Defence and Science, and MBDA have all collaborated with the Ministry of Defence on such projects, but the Ministry's favoured contractors in the sector appear to be BAE Systems, QinetiQ, and the Thales Group.

BAE Systems

BAE Systems is the world's fourth largest arms producer.[92] Despite having extensive US interests its headquarters remain in the UK and the company considers the UK to be one of its key home markets. With a product range which includes fast jet fighter aircraft and missiles, it is well placed to move into the development of autonomous air systems, and particularly large-scale systems rather than micro-drones. The company has collaborated in research programmes funded by the Defence Science and Technology Laboratory (see section 4.1 above) and also has its own in-house programmes which are often based on partnerships with other defence industry contractors, small and medium enterprises with specialist knowledge, and universities.

BAE Systems appears to have been involved in the development of autonomous unmanned aircraft since around the turn of the century. Smaller drone projects named Kestrel, Raven, Corax, and Herti have paved the way for subsequent larger demonstrator programmes intended to pioneer the development of various aspects of autonomous flight and surveillance technology.[93] Since then BAE Systems has led the following autonomous aircraft programmes:

Mantis

Development of the Mantis medium altitude long endurance UAV began in 2007, with joint funding from BAE Systems and MoD. The aircraft was intended as a demonstrator programme to establish an indigenous UK capability to integrate the technologies required for a persistent UAV able to conduct

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91   Heather-Fiona Egan: 'Accelerating innovation in defence and security'. Civil Service Quarterly blog. 28 March 2018. https://quarterly.blog.gov.uk/2018/03/28/accelerating-innovation-in-defence-and-security/

92   2016 figures. 'SIPRI Arms Industry Database', Stockholm International Peace Research Institute. Spreadsheet at https://www.sipri.org/databases/armsindustry

93   Tim Mahon: 'U.K., BAE Systems Divulge Details on Six UAV Programs'. SpaceNews, 17 April 2006. http://spacenews.com/uk-bae-systems-divulge-details-six-uav-programs/

intelligence, surveillance, target acquisition, and reconnaissance (ISTAR) operations similar to the Reaper drone. Mantis reportedly included high levels of system autonomy and part of the programme aimed to evaluate autonomous control systems.[94]

ASTRAEA

The ASTRAEA (Autonomous Systems Technology Related Airborne Evaluation and Assessment) programme commenced in 2006 with the aim of developing technologies, systems, facilities, procedures and regulations to allow autonomous unmanned vehicles to operate safely in UK civil airspace. The programme was a joint government – industry initiative, led by a consortium consisting of Airbus Defence and Space, AOS Group, BAE Systems, Cassidian, Cobham plc, EADS, QinetiQ, Rolls-Royce and Thales, with input from a large number of specialist companies and universities. During a series of test flights, a modified BAE Jetstream aircraft was equipped as a UAV and flown remotely by a satellite link, using sensing technologies to avoid aircraft and clouds. The project concluded in 2013 when government funding ceased, but in 2016 BAE commenced a further phase of self-funded development work to take forward concepts developed during the first parts of the programme.[95]

Magma and Demon

In December 2017 BAE Systems unveiled its Magma experimental drone. The Magma drone is a small-scale jet powered drone which uses an innovative blown air system to manoeuvre the aircraft. The system is trialling two new types of technology as an alternative to the conventional mechanical elevators and ailerons that are normally used to control aircraft movement. These are wing circulation control, which takes air from the aircraft engine and blows it supersonically through the trailing edge of the wing to provide control for the aircraft, and fluidic thrust vectoring, which uses blown air to deflect the exhaust, changing the direction of the aircraft. The new systems are intended to provide a stealthier profile for the drone as they do not rely on moving parts or trailing edges. The Magma project is being conducted by BAE in partnership with the University of Manchester, with input from the NATO Science and Technology Organisation and the University of Arizona.[96]

Magma builds on technology developed in an earlier experimental system – the Demon drone, which first took to the air in 2009 and used a similar air jet system for manoeuvring. Demon was built with assistance from Cranfield University and nine other UK universities. It was funded jointly by BAE Systems and the EPSRC through the £6.2 million Flapless Air Vehicle Integrated Industrial Research (FLAVIIR) five-year research programme. Although Demon was controlled by a human operator, the drone showed a degree of autonomy in its flight control system which was based around flight control algorithms developed at Leicester University and Imperial College.[97]

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94 'Mantis. Deep & Persistent ISTAR'. BAE Systems factsheet, December 2011. www.baesystems.com/en/download-en/20151124130114/1434562186815.pdf

95 'Surrogate UAV prepares for maiden flight in UK airspace'. BAE Systems news release, 18 June 2012. https://www.baesystems.com/en-uk/article/surrogate-uav-prepares-for-maiden-flight-in-uk-airspace

'Engineers begin next phase of unmanned aircraft technologies trials in flying testbed'. BAE Systems news release, 13 December 2016. https://www.baesystems.com/en/article/engineers-begin-next-phase-of-unmanned-aircraft-technologies-trials-in-flying-testbed

96 'Successful flight trial completion of unmanned aerial vehicle, MAGMA'. BAE Systems news release, 13 December 2017. https://www.baesystems.com/en/article/first-magma-flight-trials

97 First flight for 'flapless' UAV. The Engineer, 1 September 2010. https://www.theengineer.co.uk/issues/september-2010-online/first-flight-for-flapless-uav/

Taranis

The Taranis supersonic stealth aircraft (see Case Study 3) is an experimental drone which has been designed by BAE to develop technology which can "hold an adversary at continuous risk of attack … penetrate deep inside hostile territory, find a target, facilitate either kinetic or non-kinetic influence upon it, assess the effect achieved, and provide intelligence back to commanders."[98] Taranis displays advanced capabilities for autonomous operation, including reportedly the ability to identify and attack targets autonomously.

Adaptable UAVs

In October 2017 BAE announced that it was collaborating with Cranfield University on the development of 'Adaptable UAVs' – a hybrid between fixed-wing and rotary-wing UAVs. When in rotary wing mode the drones can be docked and launched like quoits from a special pole.

The system, designed for military use, would display a high degree of autonomy, employing adaptive flight control and advanced navigation and guidance software and being capable of machine-machine teaming operations to allow it to tackle air defences and operate in complex urban environments. Although mock-up images showing the Adaptable UAV concept have been published, as yet no information about real life demonstrator aircraft is available.[99]

The Taranis autonomous stealth drone during flight trials at Woomera, Australia. **Credit** BAE Systems

Other programmes

As well as working on the development of autonomous UAVs, BAE Systems is also investing significantly in other fields important in the development of autonomous weapon systems such as artificial intelligence and sensor technology. Much of this work is conducted by BAE Systems Technology

98   'Taranis unveiled – how the 'god of thunder' will shape future thinking'. Desider, August 2010, Issue 27.
       https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/33838/desider_27_August2010.pdf
99   'Engineers unveil futuristic unmanned aircraft concept that uses both fixed and rotary wing flight'. BAE Systems news release, 29 September 2017. http://www.baesystems.com/en/article/engineers-unveil-futuristic-unmanned-aircraft-concept-that-uses-both-fixed-and-rotary-wing-flight

Services and Solutions Inc in the United States. The division's Special Activity Exploitation (SAX) research group works closely with government research labs and organizations, including the Defense Advanced Research Projects Agency (DARPA) and the Intelligence Advanced Research Projects Agency (IARPA). The group leads BAE's work with these agencies on the invention and application of machine learning, control, and optimization approaches to learn patterns of behaviour from data sources, including real-time sensor feeds, to detect changes and anomalies, predict behaviour, and recognise complex events and activities.[100] Within the Intelligent Adaptive Software (IAS) directorate, research is conducted into computer science, software engineering, and artificial intelligence for autonomous systems.[101] The Video, Image, and Spectral Exploitation (VISX) directorate works on revolutionary video and image processing technology including automatic target recognition and the specific sub-fields of image processing and fusion, target signature generation, modelling and simulation, and object recognition and classification.[102]

Among the work that these teams have been involved in is:

- The development of activity-based intelligence tools which use computer-based machine learning approaches for the analysis of very large volumes of digital intelligence;[103]
- Contract work for DARPA on 'cognitive electronic warfare' technology which uses artificial intelligence and machine learning to detect, identify, and counter an enemy's electronic signals, such as radar or jamming signals;[104]
- Development of wide area persistent surveillance systems, notably the Autonomous Real-Time Ground Ubiquitous Surveillance Imaging System (ARGUS-IS). ARGUS-IS is an advanced camera system giving a resolution good enough to track people and vehicles over a wide area.

Case Study 3 Taranis: BAE's autonomous stealth drone

The Taranis unmanned combat air system represents the culmination of more than a decade's work by BAE Systems and the Ministry of Defence to demonstrate developing autonomous and stealth technology which could be used in a future lethal autonomous drone. Taranis has been described by the Ministry of Defence as a "fully autonomous" aircraft and Lord Drayson, minister for defence procurement from 2005-2007, has said it would have "almost no need for operator input."[105]

Over £200 million has been spent on the Taranis programme since it commenced in 2006, with half provided by the Ministry of Defence and half provided by industry.[106] The Ministry of Defence told the House of Commons

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100 'Machine Learning Scientist II'. BAE Systems job advertisement, 18 December 2017. https://jobs.baesystems.com/global/en/job/BAE1US133/Machine-Learning-Scientist-II

101 'Sr. Principal Research Scientist – Advanced Computing'. BAE Systems job advertisement, 27 December 2017. https://jobs.baesystems.com/global/en/job/BAE1US4722/Sr-Principal-Research-Scientist-Advanced-Computing

102 'Technology Development Manager – Automatic Target Recognition'. BAE Systems job advertisement, 9 January 2018. https://jobs.baesystems.com/global/en/job/BAE1US5138/Technology-Development-Manager-Automatic-Target-Recognition

103 'Activity Based Intelligence (ABI)'. BAE Systems webpage. https://www.baesystems.com/en-us/our-company/inc-businesses/intelligence-and-security/capabilities-and-services/actionable-intelligence/activity-based

104 Matt Cox: 'BAE Expands Work on Electronic Warfare Tech for DARPA'. Defensetech, 4 November 2016. https://www.military.com/defensetech/2016/11/04/31507

105 Jon Cartwright, 'Rise of the Robots and the Future of War'. The Guardian, 21 November 2010. https://www.theguardian.com/technology/2010/nov/21/military-robots-autonomous-machines

106 Ministry of Defence. Response to Freedom of Information Act request FOI2018/01193, 21 February 2018.

Defence Committee in 2008 that the Taranis programme was intended to "address a range of technology issues including low observable signature technology integration, vehicle management (including autonomous operation), sensor and payload integration, air vehicle performance, command and control and communications integration."[107] The drone is capable of "undertaking sustained surveillance, marking targets, gathering intelligence, deterring adversaries and carrying out strikes in hostile territory," according to the Ministry of Defence.[108]

The Taranis programme was managed by the Defence Equipment and Support Unmanned Air Systems team within the Ministry of Defence. BAE Systems was appointed as the prime contractor and industry lead for the "informal partnership" responsible for developing Taranis. BAE has provided stealth technology, systems integration, control infrastructure, and, working with QinetiQ, autonomous elements of the programme, while Rolls-Royce has provided propulsion installation and GE Aviation has developed vehicle systems for the aircraft.[109]

Ground tests for Taranis took place at BAE's Warton aerodrome in 2010, with the first two phases of flight trials taking place at the Woomera test range in Australia in 2013-14 and a third phase commencing in 2015. The drone is intended to be a demonstrator aircraft, for experimenting with technologies that may be used in future aircraft, rather than scheduled for development into a production aircraft.

Taranis is able to perform a significant number of operations autonomously without pilot input. Promotional material published by BAE states that Taranis is capable of flying to a target area via a pre-programmed flight path, relaying intelligence en route to mission command. It is then capable of searching the target area to identify individual targets for verification by mission command.[110] More detail has been revealed by Jon Wiggall, BAE's lead flight-test engineer for Taranis, who spoke to Flight Global magazine in 2016 about the aircraft's autonomous capabilities.[111] Taranis is able to taxi to a runway "entirely automatically", then take off and fly in one of three flight modes. The primary mode for take-off, general flying and landing is the automatic flight mode in which it follows marked waypoints in a similar way to the autopilot on a commercial airliner. In autonomous mode, used when searching for targets, the aircraft "starts to think and self-navigate." The aircraft self-plots a route and will fly around until either it has completed its mission or is instructed to return to base. During flight tests in autonomous mode the drone was presented with an area inside a test range in which it was required to locate a target. Taranis "can self-navigate within a boundary of set constraints," according to Wiggall. "It does have limitations on what we give it in the mission plan – it can only fly in certain areas – but it does think for itself, it will navigate, and it will search for targets." The third flight mode is manual flight, used as a back-up fail-safe mode for use in the event

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107 'The contribution of Unmanned Aerial Vehicles to ISTAR capability: Government response to the Committee's Thirteenth Report of Session 2007-08'. House of Commons Select Committee on Defence. HC1087. 21 October 2008. Paragraph 23. https://publications.parliament.uk/pa/cm200708/cmselect/cmdfence/1087/108704.htm

108 'First flight trials of Taranis aircraft'. Ministry of Defence news story, 5 February 2014. https://www.gov.uk/government/news/first-flight-trials-of-taranis-aircraft--4

109 'Taranis unveiled – how the 'god of thunder' will shape future thinking', op cit.

110 'Taranis – looking to the future'. BAE Systems information leaflet. https://www.baesystems.com/en/download-en/20151124120336/1434555376407.pdf

111 Beth Stevenson: 'Analysis: Taranis developers reveal test flight specifics'. Flight Global, 16 May 2016. https://www.flightglobal.com/news/articles/analysis-taranis-developers-reveal-test-flight-spec-425347/

of unexpected circumstances – though this mode of flight was apparently rarely used during the Taranis flight trials.

Taranis also appears to have the capacity to identify and attack targets autonomously. In an interview with the Daily Express about the aircraft, BAE's Taranis Programme Manager, Clive Marrison, pointed out that although it was "highly likely" that the UK's Rules of Engagement would continue to require a human to determine target decisions, "the Rules of Engagement could change,"[112] and the project was proceeding on the basis that an autonomous strike capability could be required in the future.[113]

QinetiQ

QinetiQ is a UK-based arms manufacturer which evolved from the Defence Evaluation and Research Agency (DERA), a Ministry of Defence agency which was privatised in 2001. QinetiQ emerged as the commercial entity resulting from privatisation, while other DERA functions were retained in-house as DSTL. QinetiQ runs a number of Ministry of Defence research sites under the terms of a Long Term Partnering Agreement – a 25-year contract to deliver test and evaluation and training support services to the UK armed forces.[114] As a result, the company has been a favoured contractor for the Ministry of Defence for the assessment and later stage development of drones and autonomous systems.

Particularly significant among the test sites operated by QinetiQ is the Wales Unmanned Aircraft Systems Environment (WUASE), located at MoD sites at ParcAberporth in Ceredigion and the Snowdonia Aerospace Centre at Llanbedr, both on the west coast of Wales.[115] These sites have a range of take-off and landing sites, targets, and radar and sensor facilities suitable for testing drones and their weapon systems and for training personnel in their operation. A number of MoD unmanned systems have been tested at these sites, including the Army's Watchkeeper surveillance drone and BAE's Magma experimental drone.

QinetiQ also hosts the Unmanned Air Systems Capability Development Centre (UAS CDC) at Boscombe Down, Wiltshire, an advisory unit which coordinates the input of support and expertise from relevant MoD agencies, industry, and academia on emerging matters relating to military drones. The UAS CDC advises on planning and best practice and provides a 'knowledge bank' of information to customers during the testing, evaluation, and development of unmanned systems.[116] Other test and evaluation sites for unmanned aerial systems are operated by QinetiQ at MoD Larkhill, MoD Shoeburyness, MoD Hebrides, and MoD West Freugh.

Under the terms of the Long Term Partnering Agreement QinetiQ was contracted by the Defence Equipment and Support Technology Office and the Royal Navy to plan and deliver Exercise Unmanned Warrior 16, the Navy's

112 John Ingham: 'WATCH: Unmanned test plane can seek and destroy heavily defended targets'. Daily Express, 9 June 2016. https://www.express.co.uk/news/uk/678514/WATCH-Video-Unmanned-test-plane-Taranis

113 James Dean: 'RAF drone could strike without human sanction'. The Times, 10 June 2016. https://www.thetimes.co.uk/article/raf-drone-could-strike-without-human-sanction-mzpjmr786 Guia Marie Del Prado: 'This drone is one of the most secretive weapons in the world'. Business Insider UK, 29 September 2015. http://uk.businessinsider.com/british-taranis-drone-first-autonomous-weapon-2015-9?r=US&IR=T

114 Long Term Partnering Agreement website. https://www.ltpa.co.uk

115 Wales Unmanned Aircraft Systems Environment website. http://www.wuase.com/

116 Unmanned Air systems Capability Development Centre website. https://www.uascdc.com/

first ever demonstration exercise for unmanned military technology.[117] The exercise took place on MoD ranges run by QinetiQ in Scotland and Wales and the company also managed logistics, communications, range management and safety arrangements for the event, during which more than 50 unmanned vehicles from 40 different organisations undertook missions in the air, on the sea, and underwater. QinetiQ also led an industry team including BAE Systems, Thales and Seebyte to provide the event's overall command and control system. Known as ACER (Autonomous Control Exploitation and Realisation), the system allows the control of a number of drones simultaneously in both the air and maritime environments and was used to plan, monitor, and execute mine-sweeping missions. DSTL has since awarded the consortium a contract to undertake a further phase of work to develop the system for integration into the combat system of a warship.[118]

QinetiQ has also been involved in the development of other unmanned systems for the Ministry of Defence. The company originally designed and built the Zephyr High Altitude Pseudo-Satellite – a new generation of drone capable of flying to heights of over 20,000 metres and loitering for extended periods of days, or even weeks. Zephyr holds the official record for the longest duration of unmanned flight, remaining in the air for 14 days during a flight in 2010, and in August 2018 exceeded this with a 25 day flight.[119] The aircraft is extremely lightweight and is powered by a combination of solar cells and rechargeable batteries and can be equipped with conventional cameras, radar and lidar sensors, and communications interception equipment.[120] It is capable of undertaking reconnaissance and security patrols, acting as a communications relay platform, and undertaking advanced surveillance work. The Zephyr system project was sold to Airbus Defence and Space in 2013 and the Ministry of Defence has since purchased three of the aircraft which are undergoing demonstrator trials with Joint Forces Command to assess their capabilities.[121]

QinetiQ leads a consortium, including Thales and BAE Systems, to deliver the unmanned aircraft systems autonomy and mission management contract for DSTL.[122] It is also involved in a number of research consortia working on various research projects as part of DSTL's Command, Control, Communications, Computers & Intelligence (C4I) & Big Data Analytics programme.[123]

Thales Group

Thales Group is a French multinational company, ranked as the tenth largest arms manufacturer in the world, with a UK based sub-division.[124] Over the last decade Thales has developed considerable experience in working with the UK Ministry of Defence on drone programmes, largely through its role as prime contractor leading the Watchkeeper drone project. Thales claims to be Europe's number one tactical UAS company, with a turnover of €1.5 billion for its UAS

117 Laura Armstrong: 'Case Study: Celebrating one year since Unmanned Warrior'. QinetiQ blog article, 20 October 2017. https://www.qinetiq.com/en-gb/blogs/2017/10/unmanned-warrior-2016-one-year-on

118 'QinetiQ leads next phase of unmanned systems exploitation'. QinetiQ news release, 16 August 2017. https://www.qinetiq.com/en-gb/news/2017/08/maple4

119 Ministry of Defence: 'Joint Forces Command Operational Concept Demonstrator flies for over 25 days'. Press release, 10 August 2018. https://www.gov.uk/government/news/joint-forces-command-operational-concept-demonstrator-flies-for-over-25-days

120 Airbus Defence and Space: 'Zephyr: the High Altitude Pseudo-Satellite'. https://airbusdefenceandspace.com/our-portfolio/military-aircraft/uav/zephyr/

121 Ministry of Defence: 'MoD buys third record-breaking UAV'. Press release, 17 August 2016. https://www.gov.uk/government/news/mod-buys-third-record-breaking-uav

122 Unmanned Air Systems'. Defence Science and Technology Laboratory, op cit.

123 Response to Request for Information FOI 2017/10715. Ministry of Defence, op cit.

124 2016 figures. 'SIPRI Arms Industry Database', Stockholm International Peace Research Institute. Spreadsheet at https://www.sipri.org/databases/armsindustry

business during the last 10 years and achievement of 100,000 hours of flying experience[125] – presumably largely as a result of Watchkeeper flights.

Watchkeeper is an intelligence, surveillance, target acquisition and reconnaissance drone based on the Israeli Elbit Systems Hermes 450 airframe and built by a joint venture company comprising of Elbit and Thales. In 2005 the Ministry of Defence ordered 54 Watchkeeper drones for the Army with the intention of deploying them for combat use in Afghanistan. The Watchkeeper programme has had a somewhat chequered history, having considerably exceeded original cost estimates and, as a result of delays in reaching operational capability, failing to achieve virtually any combat experience in Afghanistan. Watchkeeper shows some degree of autonomous capability in its operation. According to Thales, it has a "fully autonomous mission control and Autonomous Take off and Landing System (ATOLS)," and "onboard autonomous emergency logic" enabling it to glide to pre-programmed emergency landing sites in the event of loss of a control link.[126]

The Army's Watchkeeper drone, jointly developed by Thales and Elbit Systems has had a chequered history and has experienced a number of crashes.
Credit Crown Copyright

Much of the Watchkeeper test and training programme has been conducted at Aberporth and in September 2017 Thales committed to invest £7 million in trials and training facilities for the development of unmanned aircraft systems at the West Wales Airport at Aberporth, and at a new maritime autonomy centre at Plymouth.[127] Thales' previous work in the field of maritime autonomy includes development of an unmanned surface vehicle able to tow a sonar array and detect and report underwater mines. Autonomous technology enables the craft to follow an optimum search grid while retaining the ability to 'see' and avoid other traffic.[128]

In addition, Thales has also developed a range of smaller drones which show some autonomous characteristics. The Spy Arrow is a hand-launched mini drone developed for military use which is in service with the French army to provide real time video imagery with geolocation points for observation and reconnaissance purposes. Spy Arrow entered production in 2009 and can be operated in either a manual assisted mode or a fully autonomous mode from take-off to landing over a pre-planned or user guided path.[129] Thales also manufacture the Spy Copter drone which is described as a "fully autonomous mini multi-role VTOL [vertical take off and landing] UAS" which is "capable of transporting several types of payload."[130]

Thales is involved in the nEUROn project to develop a European unmanned combat aircraft stealth technology demonstrator. The company has designed the data link communication system which allows transmission of command and control data and sensor data, and a GPS hybrid military inertial system for nEUROn, which precisely identifies the drone's position and altitude.[131] In addition, the company has worked alongside other industry partners in various consortia aimed at developing autonomous drone technology, such as BAE's Mantis project.

125 'Unmanned Aerial Vehicles systems'. Thales Group website article. https://www.thalesgroup.com/en/global/activities/defence/unmanned-aerial-vehicles-systems

126 'Watchkeeper'. Thales Group website article. https://www.thalesgroup.com/en/global/activities/defence/unmanned-aerial-vehicles-systems/tactical-uav

127 'Thales invests in two new UK-based trials and training centres for autonomous systems'. Thales Group news release, 12 September 2017. https://www.thalesgroup.com/en/worldwide/defence/press-release/thales-invests-two-new-uk-based-trials-and-training-centres

128 'How we already rely on artificial intelligence'. Thales Group website article, 10 January 2018. https://www.thalesgroup.com/en/united-kingdom/news/how-we-already-rely-artificial-intelligence

129 Gary Mortimer: 'Thales Spy Arrow'. sUAS News, 10 September 2010. https://www.suasnews.com/2010/09/thales-spy-arrow/

130 'Systems and solutions for unmanned aerial vehicles'. Thales Espana. https://www.thalesgroup.com/sites/default/files/asset/document/folleto-uas-ing.pdf

131 NEUROn Unmanned Combat Air Vehicle (UCAV) Demonstrator. Air Force Technology website. http://www.airforce-technology.com/projects/neuron/

4.4 Academia

The world's leading universities are also engaged in cutting edge research in the fields of artificial intelligence, robotics, and autonomous systems. A number of UK universities are conducting research into artificial intelligence, autonomous technology, and drones. The Stockholm International Peace Research Institute has rated three British universities in its top ten global research institutes in the field of artificial intelligence, based on the volume of their academic publications on relevant topics over the period 2011-16.[132] These are University College London (artificial intelligence and human-machine interaction), Newcastle University (human-machine interaction), and the University of Edinburgh (natural language processing). One British university appeared in a similar list for the field of robotics – Imperial College was included in the list of institutes with the most publications about autonomous systems.

The EPSRC supports the UK Robotics and Autonomous Systems network, which aims to provide academic leadership in the sector, expand collaboration with industry and integrate and coordinate activities between participating universities. The EPSRC also funds networks and initiatives aimed at promoting co-operation between universities and the military in areas relating to artificial intelligence and data processing. Five UK universities – Cambridge, Edinburgh, Oxford, University College London, and Warwick – have collaborated to establish the national institute for data science, the Alan Turing Institute, with support from the ESPRC. The Institute was opened in 2015 with £42 million in investment, and is headquartered in the British Library. It aims to bring together researchers in mathematics, statistics, computer science, social science and data ethics, software engineering, machine learning and artificial intelligence to generate world class research in data science. One of the Institute's core areas of research is defence and security, and it has entered into a strategic partnership with GCHQ, which presumably already has considerable experience in the field, together with access to large quantities of data, and with the Ministry of Defence, through DSTL and Joint Forces Command, which is responsible for defence intelligence and information systems. The partnership is "interested in developing data science methodologies and techniques, and in the direct application of data science".[133] Eight universities also work as a consortium as part of the University Defence Research Collaboration, a £8 million joint venture between the MoD and ESPRC aimed at using academic research to boost military capabilities.[134] The current phase of collaboration is based around signal processing, and using algorithms to interpret and create images from sensor data, such as signals from synthetic aperture radar, sonar, and spectral imaging.

Cranfield University has considerable expertise in aeronautical engineering and is a frequent collaborator with military contractors. Cranfield is one of BAE Systems' Strategic University Partners, of which there are five in total, the others being the Universities of Birmingham, Manchester, Southampton, and Strathclyde.[135] Similarly, the University of Bristol is a strategic university partner of Thales Group.[136] The partnership is mainly focused on the university's

132 Vincent Boulanin and Maaike Verbruggen: 'Mapping the development of autonomy in weapon systems'. Stockholm International Peace Research Institute. 2017, Tables G and H, P130-1.

133 'Founding Members'. Alan Turing Institute website. https://www.turing.ac.uk/governance/

134 University Defence Research Collaboration. https://udrc.eng.ed.ac.uk/

135 BAE Systems: 'Collaborating with academia to develop new technologies'. News release, 21 April 2017. https://www.baesystems.com/en-uk/article/collaborating-with-academia-to-develop-new-technologies

136 University of Bristol: 'Strategic agreement set to tackle technology challenges'. News release, 9 March 2017. http://www.bristol.ac.uk/news/2017/march/thales-agreement.html

Engineering Faculty, and the research programme is intended to focus on autonomy, sensors, security, complex systems, security, and communications.

Universities appear usually to undertake applied research of this nature in collaboration with private sector contractors, often as part of a broad industry-academia consortium involving several partners from each sector, with projects specifically focused on defined outputs. Collaboration with universities provides the contractor with access to specialist research facilities that can be used to test and evaluate new designs, such as the multi terrain aerial robotics arena at Imperial College or the autonomous vehicles laboratory at Cranfield University, as well as to advanced instrumentation and equipment and the technical expertise of university staff.

Researchers at Cranfield University have worked with BAE Systems to develop the Demon demonstrator drone. **Credit** Cranfield University

A survey undertaken by Drone Wars UK using the Freedom of Information Act (see Appendix II) revealed that a number of UK universities are undertaking research work on autonomous systems and big data analytics in collaboration with DSTL, BAE Systems, Thales, and QinetiQ. Particular areas of interest are sensor development and image processing, and the control and performance of autonomous systems. Some of the universities involved are Cranfield University (autonomous systems), Imperial College (sensors and data analytics), Loughborough University (autonomous systems), University College London (imaging and sensors), the University of Cambridge (control and performance), and the University of Liverpool (ship-launched drones). Selected examples of projects undertaken include:

- Novel power generation and energy management using hydrogen pellet system: work undertaken by Cranfield university for BAE systems as part of the DSTL-funded ASUR programme.
- Enabling Technologies for "UAV Array" Signal Processing: a DSTL-funded project at Imperial College.
- Maintaining Network Connectivity and Performance Using UAVs for Multi-Layer ISR System: work undertaken by Loughborough University for BAE Systems as part of the DSTL-funded ASUR programme.
- Scalable video super-resolution and fusion: work undertaken at University College London (funding source unknown).
- Ship-Board Launch and Recovery of an Unmanned Autonomous Air System: Surviving the Ship Air Wake: a BAE Systems-funded project at the University of Liverpool.

In some cases, these research projects may be sensitive – and controversial. In response to one of our requests for information, Imperial College told us that they were unable to provide details of three projects under way in the College's Department of Electrical and Electronic Engineering which we understand relate to sensor networks and visualisation. The projects are funded by DSTL, which informed the College that the three project titles were sensitive and that their release would be likely to prejudice the capability, effectiveness or security of the UK armed forces. They argued this was because the information provides an indication of the direction of research which could potentially lead to future capability being revealed, providing an advantage to enemies of the UK.

Case Study 4 Collateral Damage Estimate Methodology: Towards and algorithm for autonomous weapon targeting?

Although the actual armaments themselves provide the most obvious and visible examples of autonomy in weapon systems, software programmes and algorithms are equally important, if not more so, in enabling the development

of these systems. One of the key functions of a truly autonomous weapon system would be the ability to make decisions about targeting and firing. If such a system was ever to be used lawfully in warfare, it would be essential to ensure it could only be directed against military objectives, and that the risk of civilian casualties was proportional to the military advantage gained. This means that software would need to be capable of establishing that the weapon was not targeting civilian objectives and that collateral damage would be eliminated or minimised. 'Collateral damage' is often used as a euphemism for civilian deaths: here we use the term according to the formal US military definition, namely "unintended or incidental damage to persons or objects which are not the intended target and are not lawful targets."[137]

Software has long existed which allows the extent of collateral damage from an attack to be estimated by military commanders. Advocates of autonomous weapons argue that it would be possible to programme a machine using similar software to assess the likelihood of incidental harm to civilians and damage to civilian objects near a target.[138]

Collateral damage estimate methodology (CDEM) developed by the US military is used by NATO forces to plan attacks and to attempt to predict and minimise casualties. The technique relies on modelling and approximation – its users accept that it is "not an exact science"[139] – and therefore uncertainties are inherent in the process and its quantitative nature may give an illusion of accuracy which may not always be justified.

The methodology is based around a five-step process (see Table 2) for quantifying and standardising collateral damage estimation which uses an algorithmic approach to assess factors such as the nature of the target, the likelihood of civilian presence, a weapon's precision, attack tactics, blast effects, and the composition of buildings.[140] Assessments at each stage in the process are based around tables derived from computer modelling, weapons testing data, and combat observations.

Table 2 The five stages of assessment for Collateral Damage Estimation Methodology (after Thurnher and Kelly).

CDE 1: Target validation / initial assessment	Establish whether the proposed target is a legitimate target for attack.
CDE 2: General / minimum target size assessment	Select appropriate munitions for the task.
CDE 3: Weaponeering assessment	Choose an appropriate mode of operation and method of attack.
CDE 4: Refined assessment	Undertake a more detailed assessment of the nature of the target to assess likely damage.
CDE 5: Casualty assessment	Estimate casualties and consider how the attack can be timed to minimise these.

137 'Joint Targeting Cycle and Collateral Damage Estimation Methodology'. General Counsel, Joint Chiefs of Staff and Defense Intelligence Agency. 10 November 2009. P11.
https://www.aclu.org/files/dronefoia/dod/drone_dod_ACLU_DRONES_JOINT_STAFF_SLIDES_1-47.pdf

138 International Committee of the Red Cross: 'Expert Meeting. Autonomous Weapon Systems: Technical, Military, Legal, and Humanitarian Aspects', op cit, p82.

139 'Joint Targeting Cycle and Collateral Damage Estimation Methodology'. General Counsel, Joint Chiefs of Staff and Defense Intelligence Agency, op cit, p 35.

140 'Joint Targeting Cycle and Collateral Damage Estimation Methodology'. General Counsel, Joint Chiefs of Staff and Defense Intelligence Agency, op cit.
Jeffrey Thurnher and Timothy Kelly: 'CDE Brief: Panel Discussion: Collateral Damage Estimation'. US Naval War College Youtube video, October 2012. https://www.youtube.com/watch?v=AvdXJV-N56A

The methodology is intended to allow targeting planners to determine the level of command at which an attack causing collateral damage must be authorised – the higher the risk of damage, the higher the command level for approval – and is not designed in itself to determine whether an attack would be proportional.

Early versions of CDEM were reportedly first used for targeting planning during Operation Desert Fox in 1998, and it is available for use as a computer software programme called Fast Assessment Strike Tool – Collateral Damage (FAST-CD), nicknamed 'Bugsplat' by its users, which can reduce the time taken to predict collateral damage from hours or even days to 15 to 30 minutes.[141] CDEM is now used across NATO and serves as the framework for NATO's emerging methodology for air-to-surface and surface-to-surface lethal operations.[142] Similar software developed more recently by the US Army's Armament Research, Development, and Engineering Center can be used for targeting multiple objectives. Quick Collateral Damage Estimation (QCDE) algorithms can be used with up to ten weapons, ten targets, and ten assets and its designers claim it can execute calculations in milliseconds with errors of less than one per cent. The software "should significantly enhance the decision making in real-time for the commanders in the battlefields" according to the designers.[143]

Such software could conceivably be further developed into algorithms which could enable an autonomous armed drone to make decisions on targeting and using weapons. According to Major Jeffrey Thurnher of the International and Operational Law Department at the US Army's Office of the Judge Advocate General, estimating the number of civilians who may be harmed incidentally as a result of an attack "is unlikely to be a challenge for autonomous systems because it is essentially a quantitative determination."[144] Although judgement of whether an attack would be proportional and legal would require a more qualitative assessment and may be technologically challenging, looking into the future "it is not inconceivable that such a mechanism could be developed and embedded into an autonomous weapon," according to Thurnher. In the meantime, he argues that autonomous weapons could be used in situations where civilians were not expected to be present or where they could be controlled by setting geographic boundaries or time limits for their operation.

Professor Michael Schmitt, Professor of International Law at the United States Naval War College has likewise argued that "there is no question that autonomous weapon systems could be programmed to perform CDEM-like analyses to determine the likelihood of harm to civilians in the target area." He considers that "military advantage algorithms" could in theory be

141 'U.S. Air Force Uses New Tools To Minimize Civilian Casualties'. Defense-Aerospace.com, 18 March 2003. http://www.defense-aerospace.com/article-view/feature/18894/usaf-plans-to-minimize-civilian-casualties.html
Bradley Graham: 'Military Turns to Software to Cut Civilian Casualties'. Washington Post, 21 February 2003. https://www.washingtonpost.com/archive/politics/2003/02/21/military-turns-to-software-to-cut-civilian-casualties/af3e06a3-e2b2-4258-b511-31a3425bde31/?utm_term=.a59a7d19959b

142 'N3-97. NATO Collateral Damage Estimation (CDE) Course). NATO School Oberammergau. http://www.natoschool.nato.int/Academics/Resident-Courses/Course-Catalogue/Course-description?ID=95

143 Zbigniew R. Bogdanowicz and Ketula Patel: 'Quick Collateral Damage Estimation Based on Weapons Assigned to Targets'. IEEE Transactions on Systems, Man, and Cybernetics: Systems. Vol. 45 Issue 5, p762–769, May 2015. http://ieeexplore.ieee.org/abstract/document/6923445/

144 Jeffrey S. Thurnher: 'Feasible Precautions in Attack and Autonomous Weapons'. In Wolff Heintschel von Heinegg, Robert Frau, and Tassilo Singer: 'Dehumanization of Warfare: Legal Implications of New Weapon Technologies', p99-118. Springer International Publishing, 2018.

programmed into autonomous weapon systems by pre-programming them to recognize a conservative "maximum collateral damage threshold" for a given military objective.[145]

It may eventually – in theory – be possible to develop software that would be able to assess all the factors needed in coming to a decision on whether an attack would qualify as proportional, but this would be extremely difficult, especially in a complex and rapidly changing environment. In the long-term future, it may be possible to develop such a system, but it is also possible that an unscrupulous state or operator could develop and deploy an autonomous armed drone with software which is not sophisticated enough to guarantee that civilians are safeguarded – or even without such software. Such a move would pose a serious challenge to the laws governing armed conflict.

4.5 Conclusion

Despite public statements that the UK "has no intention of developing" lethal autonomous weapon systems,[146] there is a tangible body of evidence that the Ministry of Defence, military industrial contractors, and universities in the UK are actively engaged in research and the development of technology which would enable weaponised drones to undertake autonomous missions. In other more militarily and economically powerful nations such as the United States, China, and Russia it can be expected that similar and even more advanced programmes are under way.

Although the technology to develop an operational fully autonomous lethal drone does not yet exist, many of the elements of the systems necessary to build such a weapon are under development. Significant elements of this technology are 'dual use' in nature, derived from civil sector applications, and thus have the potential to enable widespread proliferation. These 'building blocks' have already allowed the development of drones with advanced autonomous capabilities such as Taranis, and the development of a truly autonomous lethal drone in the foreseeable future is now a real possibility.

The next part of the report looks at the likely course of development for such drones, and some of the political, ethical, and legal issues associated with their development.

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145   Michael N. Schmitt: 'Autonomous Weapon Systems and International Humanitarian Law: A Reply to the Critics'. Harvard Law School National Security Journal, 5 February 2013. http://harvardnsj. org/2013/02/autonomous-weapon-systems-and-international-humanitarian-law-a-reply-to-the-critics/
146   Ministry of Defence: Development, Concepts and Doctrine Centre: 'Unmanned Aircraft Systems', op cit. P15.

5

Playing with fire?

Risks posed by autonomous drone technology

The use of new technologies will always have unforeseen consequences: some positive, some negative. In the case of lethal autonomous drones, combining the highly complex nature of the technology with a self-governing capability would pose risks that would be qualitatively different to the risks posed by weapon systems which have a human in the loop.

5.1 Unpredictable behaviour

Unpredictability is an inherent feature of artificial intelligence and self-learning computer systems because we do not necessarily understand how they work. Decision-making by such systems is derived largely from processes which have evolved, rather than been programmed by humans. Decisions will therefore be based on opaque logic, lacking a clear chain of analysis, and it may not be possible for humans to validate them.[147] Another source of this unpredictability is programming errors: only one digit in a line of code needs to be in error to prevent a computer application from working properly. Even if every single piece of code is entered correctly, another source of unpredictability is the potential for bias. Algorithms give the illusion of being unbiased but they are written by people and trained on socially generated data, which can encode and amplify human biases with undesired consequences.

This raises real problems, because it may not be possible to fully trust the outputs of an autonomous system which relies on machine learning systems. Although this may not be important in some uses, in high-stakes applications such as lethal autonomous drones it is a serious concern: weapons that kill must not be unpredictable.

There are already examples of how unpredictable algorithmic behaviour has had undesirable consequences in other arenas. On the world's stock exchanges, 'flash crashes' – rapid, deep, and volatile falls in security prices

> It may not be possible to fully trust the outputs of an autonomous system which relies on machine learning systems

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147 Will Knight: 'The Dark Secret at the Heart of AI'. MIT Technology Review, 11 April 2017. https://www.technologyreview.com/s/604087/the-dark-secret-at-the-heart-of-ai/

over a very short time period – have occurred as a result of unexpected feedback loops resulting from the use of algorithms to buy and sell shares.[148] An experiment by Facebook to develop a 'chatbot' artificial intelligence programme able to talk to people resulted in two of the bots unexpectedly developing their own language to communicate. The bots were able to conclude negotiations between themselves using the language, which was incomprehensible as English.[149]

Unpredictable behaviour by a lethal autonomous drone could include misidentification of targets, including undertaking attacks on civilians or friendly forces, or, even more seriously, actions which unintentionally initiate engagements or escalate conflict. The drone might also face new situations it had not been tested for, with an unknowable outcome.

Weapon systems have a destabilizing impact if, in a crisis, they would add significant incentives to initiate an attack, and particularly to attack quickly before there is time to evaluate the situation. Because of the rapidity with which autonomous weapon systems can operate, they would pose particular dangers in a crisis situation, where the risk of a misjudgement or false move could lead to escalation of conflict, probably with serious consequences.[150]

5.2 Loss of command and control

Even though lethal autonomous drones of the future would be able to operate largely independently, there would still need to be some degree of human command and control to ensure they remained within their operating parameters. Loss of control of an autonomous drone might occur as a result of a loss of communication, or, more seriously, as a result of human intervention through jamming, hacking, or spoofing of the system. A successful cyber attack on an autonomous weapon system could be potentially very serious, particularly if undetected by the system's operators. Under such circumstances it could technically be possible to modify the system so that it did not obey commands – or even launched attacks on friendly forces. High standards of communications security and cyber security are therefore essential when operating autonomous weapons.

Spoofing a system requires fooling it into making errors by presenting it with falsified information, on the basis of which it will make an incorrect decision. It is possible to 'poison' data or take advantage of flaws in algorithms to cause a computer system to malfunction in a way that is not only unpredictable, but may be difficult for the operator to detect.[151] This leaves open the possibility that vulnerabilities in software could be exploited by an opponent using "counter-AI" capabilities.

It is also possible to sabotage an artificial intelligence system by interfering with the process through which the system 'learns' to identify and recognise targets. The machine learning process needs to be carefully planned and executed using meaningful data to prevent errors from occurring. Clearly, if

148 Economist: 'One big, bad trade'. 1 October 2010. https://www.economist.com/blogs/newsbook/2010/10/what_caused_flash_crash

149 Andrew Griffin: 'Facebook's Artificial Intelligence Robots Shut Down After They Start Talking To Each Other In Their Own Language'. Independent, 31 July 2017. https://www.independent.co.uk/life-style/gadgets-and-tech/news/facebook-artificial-intelligence-ai-chatbot-new-language-research-openai-google-a7869706.html

150 Jürgen Altmann and Frank Sauer: 'Autonomous Weapon Systems and Strategic Stability'. Survival, Vol 59:5, op cit.

151 A. Nguyen, J. Yosinski, and J. Clune: 'Deep neural networks are easily fooled: High confidence predictions for unrecognisable images'. University of Wyoming Evolving Artificial Intelligence Laboratory, 2015. http://www.evolvingai.org/fooling

the learning data is of poor quality, the reliability of the system will also be poor. Machine learning inputs that an attacker has intentionally designed to cause a computer to make a mistake, known as 'adversarial examples', could be used as 'optical illusions' to fool autonomous weapons.[152] Adversarial examples are hard to defend against for the same reasons that unpredictability is an inherent feature of machine learning systems: we do not understand how the computer learning and decision making process take place, so it is difficult to come up with a solution to attempts to subvert them.

5.3 'Normal' accidents

Complex systems such as autonomous weapon systems are intrinsically vulnerable to 'normal accidents.' The features of complex systems – tight coupling (where components are linked together and closely dependent on each other), unexpected interactions, and the incomprehensibility of the system – mean that accidents will be inevitable over a long enough period of time. In such systems the risk of accidents can be reduced, but it can never be entirely eliminated.[153]

During the Iraq War in 2003 the US Army's Patriot air defence system, a complex and highly automated weapon system, was involved in two 'friendly fire' incidents which can be explained by normal accident theory.[154] The first incident occurred on 24 March 2003, when a US Patriot battery shot down a Royal Air Force Tornado aircraft, killing the crew. The Patriot misidentified the Tornado as an anti-radiation missile, and an 'identification friend or foe' system intended to prevent such accidents malfunctioned. On their own, these two failures should not have resulted in the aircraft being shot down, as the Patriot was operating in a semi-autonomous mode requiring human approval before engagement. Unfortunately, the human operator accepted the Patriot's incorrect identification of the aircraft and authorized the engagement.

Following the first incident, Patriot systems were kept in a standby mode to prevent further similar accidents. The second incident occurred shortly afterwards, on 2 April 2003, when a Patriot shot down a US Navy F18 Hornet aircraft. A Patriot battery identified an incoming track from a ballistic missile. The signal was later identified as false, but the operator was not aware of this and brought the system to a "ready" status to prepare for an engagement. The battery was in an auto-fire, not a semi-autonomous, mode which meant that when at the ready, it was authorized to engage any active threats. Once the system came to the ready, the Patriot battery fired and shot down the F-18, which was in the vicinity.

Both Patriot accidents had multiple causes: some human and some machine related. Military researchers analysing these incidents identified two main causes: 'undisciplined automation' where too many functions of a weapon system are automated without full addressing how operators can properly monitor the process and override the system if necessary; and 'automation bias' whereby operators 'naively' place too much trust in the automated capabilities of the weapon system. Accidents can also arise in the opposite

152 Open AI blog: 'Attacking Machine Learning with Adversarial Examples'. 24 February 2017.
     https://blog.openai.com/adversarial-example-research/
153 Charles Perrow: 'Normal Accidents: Living with High-Risk Technologies'. Princeton University Press, 1999.
154 Paul Scharre: 'Autonomous Weapons and Operational Risk'. Centre for a New American Security,
     February 2016. https://s3.amazonaws.com/files.cnas.org/documents/CNAS_Autonomous-weapons-
     operational-risk.pdf?mtime=20160906080515

situation, where operators under-trust a system and place insufficient reliance on an automated process.

A tragic example of this was the shooting down of an Airbus A300 passenger aircraft, Iran Air Flight 655, and the loss of 290 lives on 3 July 1988 by the automated Aegis air defence system on the USS Vincennes. The Aegis system detected Flight 655 and notified the crew that it was emitting signals on a civilian frequency and climbing. The warship's crew, however, decided that the signals were from a combat aircraft descending to attack and decided to shoot it down.[155]
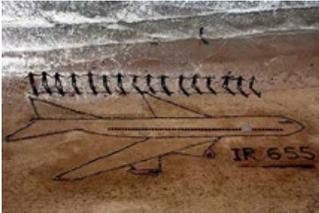
Beach art at the Environmental Art Festival, Iran, 2008, to remember the 30th anniversary of the shooting down of flight Iran Air 655 by the USS Vincennes.
Credit Raheleh Zomorodinia, Mithra Soltani, Mohamad Saybani and Ahmad Nadalian / RiverArt.net

These incidents demonstrate that human supervision does not necessarily guarantee that accidents involving automated systems will be avoided and can, in fact, add to problems if personnel are not properly trained or disciplined, or if the information provided by the system is too complex for an operator to interpret rapidly, or if the operators are facing stressful situations.

With an accident involving a futuristic autonomous weapon system, the damage caused before a human controller is able to intervene could be considerable. The lethality of accidents involving automated weapon systems is illustrated by the example of a malfunction of a 35 mm anti-aircraft weapon in 2007 during a training exercise by the South African National Defence Force.[156] The weapon failed in automatic mode, killing 9 soldiers and seriously injuring 14 others.

Like all normal accidents, the examples given here could be considered freak occurrences. But this is the nature of normal accidents, which are unpredictable and unavoidable. Human-machine teaming, often cited as a strategy for reducing the risks associated with autonomous weapons, does not eliminate these risks and under some circumstances may add a further level of complexity and scope for error.

5.4 Misuse

Autonomous weapon systems and lethal autonomous drones may be designed with a range of safety features intended to ensure that they can only be used for specific purposes. There may be strict orders, procedures, and rules of engagement to control their use. Nevertheless, experience suggests that eventually such a system will be misused for a purpose for which it was not intended.

> The deployment of autonomous weapons could commence in uncluttered environments but gradually 'creep' into more complex ones

"Humans have a poor track-record of predicting the full range of benefits or risks associated with new technologies," according to a report by the United Nations Institute for Disarmament Research.[157] "Often technologies are developed for one set of tasks but then adopted in other fields for missions not envisaged by the designers or proponents." The report identifies concerns that the deployment of autonomous weapons could commence in uncluttered environments but gradually 'creep' into more complex ones without taking into account the different situation and the potential of an

155 Vincent Boulanin and Maaike Verbruggen: 'Mapping the development of autonomy in weapon systems'. Stockholm International Peace Research Institute, op cit. P40.
Elisa B. Kania: 'The critical human element in the machine age of warfare'. Bulletin of the Atomic Scientists, 15 November 2017. https://thebulletin.org/critical-human-element-machine-age-warfare11277#

156 Noah Shactman: 'Robot Cannon Kills 9, Wounds 14,' Wired.com, 18 October 2007. www.wired.com/dangerroom/2007/10/robot-cannon-ki/

157 United Nations Institute for Disarmament Research (UNIDIR): 'Framing Discussions on the Weaponization of Increasingly Autonomous Technologies', op cit. P8.

increased risk of harm to non-combatants. Humans, including armed forces in battle environments, also "have a tendency to manipulate and modify technologies to overcome safety features and controls."

Peter Singer, author of *Wired for War*, has pointed out that human factors are often neglected during decision making on weapons technology, noting that "too often in discussions of technology we focus on the widget. We focus on how it works and its direct and obvious uses. … Indeed, with robotics, the issues on the technical side may ultimately be much easier to resolve than dilemmas that emerge from our human use of them."[158]

158 Peter Singer: 'The Robotics Revolution'. Brookings Institution, 11 December 2012, www.brookings.edu/research/opinions/2012/12/11-robotics-military-singer. Cited in United Nations Institute for Disarmament Research (UNIDIR): 'Framing Discussions on the Weaponization of Increasingly Autonomous Technologies', op cit. P8.

6 Where we're at

Why UK government policy on lethal autonomous drones needs to change

This report has demonstrated that, far from belonging in the realm of science fiction, the technology needed to build autonomous weapon systems is currently under development in a number of nations, including the United Kingdom. Because of recent advances in unmanned aircraft technology, it is likely that the first autonomous weapons will be drone-based systems and we are already beginning to see the combining of relevant technological building blocks.

In the short term it is likely that the military applications of autonomous technology will be in low risk areas, such logistics and the supply chain, where, proponents argue, there are cost advantages and minimal implications for combat situations. These systems are likely to be closely supervised by human operators. In the longer term, as technology advances and artificial intelligence becomes more sophisticated, autonomous technology is increasingly likely to become weaponised and the degree of human supervision can be expected to drop. This is where serious problems can be expected to arise: the higher the reasoning powers of autonomous weapons, the more likely they are to start making unpredictable decisions and failing to comply with instructions.

The real issue perhaps is not the development of autonomy itself but the way in which this milestone in technological development is controlled and used by humans. Autonomy raises a wide range of ethical, legal, moral and political issues relating to human judgement, intentions, and responsibilities.[159] These questions remain largely unresolved and there should therefore be deep disquiet about the rapid advance towards developing lethal autonomous weapons systems.

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159 Such issues are covered comprehensively in:
International Committee of the Red Cross: 'Autonomous Weapon Systems: Technical, Military, Legal and Humanitarian Aspects'. Report of Expert Meeting, 26-28 March 2014, op cit.
United Nations Institute for Disarmament Research (UNIDIR): 'Framing Discussions on the Weaponization of Increasingly Autonomous Technologies'. 2014, op cit.
United Nations Educational, Scientific, and Cultural Organisation and World Commission on the Ethics of Scientific Knowledge and Technology: 'Report of COMEST on Robotics Ethics'. 14 September 2017. unesdoc.unesco.org/images/0025/002539/253952E.pdf

6.1 How the UK fits in to the global picture

Despite the seeming inevitability of the development of lethal autonomous drones there are a range of measures which could be used to prevent this: establishing international treaties, norms, developing confidence-building measures, introducing international legal instruments, and adopting unilateral control measures. Drone Wars UK takes the view that the UK should be fully involved in helping to develop such control measures.

At the present time, the US and the UK are the only nations to have adopted detailed government policies on autonomous weapon systems. The policies of both countries are limited in scope and aim to restrict the deployment of autonomous weapons without appropriate human control, yet, at the same time allow research into autonomous weapons to move forward.

The UK government's policy on lethal autonomous weapons is set out in a Joint Doctrine Publication, 'Unmanned Aircraft Systems', and a Joint Concept Note, 'Human-Machine Teaming'[160], published in September 2017 and May 2018 respectively by the Ministry of Defence's Development, Concepts, and Doctrine Centre. The Joint Doctrine Publication argues that the UK currently operates its military drones in compliance with national and international law. It states that the UK opposes the development of armed autonomous systems[161] and has no intention of developing autonomous weapon systems, as it wants commanders and politicians to act as decision makers and retain responsibility.[162] These statements sound reassuring – as they have been designed to be – but it is worth examining policies in more detail to clarify exactly what the government is, and is not, committing to.

The first problem arises in clarifying what exactly the government means when it is discussing autonomous weapon systems. The Joint Doctrine Publication states that "Fully autonomous weapons systems as we describe them (machines with the ability to understand higher-level intent, being capable of deciding a course of action without depending on human oversight and control) currently do not exist and are unlikely in the near future," if at all. [163] The Ministry of Defence has been accused of 'defining away' the problems associated with autonomous weapons by setting such a high threshold of technical capability to define them.[164] Hayley Evans, writing on the influential Lawfare blogsite, concluded that "the U.K. defines autonomous weapons systems and LAWS in such a futuristic way that it is difficult to discern the U.K. position on other, less sophisticated LAWS that are actually on the cusp of development."[165] Because the bar has been set so high, in other words, the definition effectively places no restrictions on anything that the UK is doing to develop autonomous weapon systems as the rest of the world understands the term. By inferring that the development of autonomous weapons is a remote possibility, adopting this

160 Ministry of Defence: Development, Concepts, and Doctrine Centre: 'Human-Machine Teaming'. Joint Concept Note 1/18, 21 May 2018. https://www.gov.uk/government/publications/human-machine-teaming-jcn-118

161 Ministry of Defence: Development, Concepts and Doctrine Centre: 'Unmanned Aircraft Systems'. Joint Doctrine Publication 030.2, 12 September 2017, op cit. P37.

162 Ministry of Defence: Development, Concepts and Doctrine Centre: 'Unmanned Aircraft Systems'. Joint Doctrine Publication 030.2, 12 September 2017, op cit. P37, p50.

163 Ministry of Defence: Development, Concepts and Doctrine Centre: 'Unmanned Aircraft Systems'. Joint Doctrine Publication 030.2, 12 September 2017, op cit. Para 4.17, p43.

164 Maziar Homayounnejad: 'A Note on the Sense and Scope of 'Autonomy' in Emerging Military Weapon Systems and Some Remarks on The Terminator Dilemma'. In 'Autonomy in Future Military and Security Technologies: Implications for Law, Peace, and Conflict'. The Richardson Institute, Lancaster University, 2017, op cit. P71.

165 Hayley Evans: 'The United Kingdom and Unmanned Aerial Vehicles: A summary of Joint Doctrine Publication 0-30.2'. Lawfare, 17 October 2017. https://lawfareblog.com/united-kingdom-and-unmanned-aerial-vehicles-summary-joint-doctrine-publication-0-302

definition allows the government to side-step questions about the need to regulate them.

The government's definition of 'autonomous weapons' has apparently been set to suit its own convenience and political position, rather than on an objective basis which is in step with the views of other states and non-government experts. The House of Lords Select Committee on Artificial Intelligence takes a similar view, describing the UK's distinction between automated and autonomous weapon systems as "relatively unusual"[166] and its definition of an autonomous system as "clearly out of step with the definitions used by most other governments."[167] The Committee felt that this position "limits both the extent to which the UK can meaningfully participate in international debates on autonomous weapons and its ability to take an active role as a moral and ethical leader on the global stage in this area," and also hamstrings attempts to arrive at an internationally agreed definition. The Select Committee recommended that the UK's definition of autonomous weapons should be realigned to be the same, or similar, as that used by the rest of the world and that this should be done by the end of 2018.[168] The government's response to the Committee, published in June 2018, stated that "the Ministry of Defence has no plans to change the definition of an autonomous system."[169]

> Far from having "no intention" to develop autonomous weapons, the MoD and its contractors are actively engaged in research which would contribute to the development of such systems

The MoD also states that the UK does not possess fully autonomous weapons and has "no intention of developing them."[170] This statement does not sit comfortably alongside endorsements for autonomous weapons from senior members of the armed forces. Speaking at the DSEI arms fair in September 2017, Rear Admiral Paul Bennett, the Royal Navy's assistant chief of staff for capability, said that the Royal Navy was "absolutely determined that we're going to embrace autonomy as the future and embrace innovation in every sense."[171] General Sir Richard Barrons, who until recently was Commander of Joint Forces Command, has said that: "The temptation to have them I think will be terrific because they will be more effective, they will be cheaper, they will take people out of harm's way and will give you bigger armed forces, so the pressure to have them will only grow. You find ways of delivering the military output that you want at much cheaper cost."[172] This study presents a body of evidence which shows that, far from having "no intention" to develop autonomous weapons, the Ministry of Defence and its contractors are actively engaged in research which would contribute to the development of such systems with decreasing levels of human control in the critical functions of selecting and engaging targets.

The claim that "the UK opposes the development of armed autonomous systems" also appears to be at odds with the evidence. Since 2015 the government has declined to support moves at the United Nations Convention

166 House of Lords Select Committee on Artificial Intelligence: 'AI in the UK: ready, willing, and able?' Report of Session 2017-19, 16 April 2018. Box 10, p102. https://publications.parliament.uk/pa/ld201719/ldselect/ldai/100/100.pdf

167 House of Lords Select Committee on Artificial Intelligence: 'AI in the UK: ready, willing, and able?', op cit. Para 345, p105.

168 House of Lords Select Committee on Artificial Intelligence: 'AI in the UK: ready, willing, and able?', op cit. Para 346, p105.

169 'Government response to House of Lords Artificial Intelligence Select Committee's Report on AI in the UK: Ready, Willing and Able?'. CM 9645, June 2018. Para. 99, p33. https://www.parliament.uk/documents/lords-committees/Artificial-Intelligence/AI-Government-Response2.pdf

170 Ministry of Defence: Development, Concepts and Doctrine Centre: 'Unmanned Aircraft Systems'. Joint Doctrine Publication 030.2, 12 September 2017, op cit. Para 2.6, P14.

171 Jon Rosamond: 'U.S. Navy Research Chief Urges Caution as British Admirals Begin Dash for Autonomy'. US Naval Institute News, 18 September 2017. https://news.usni.org/2017/09/18/u-s-navy-research-chief-urges-caution-british-admirals-begin-dash-autonomy

172 Ben Farmer: 'Prepare for rise of 'killer robots' says former defence chief'. Daily Telegraph, 27 August 2017. https://www.telegraph.co.uk/news/2017/08/27/prepare-rise-killer-robots-says-former-defence-chief/

on Certain Conventional Weapons aimed at banning autonomous weapon systems. Along with France, Israel, Russia, and the United States, the UK has explicitly rejected moving to negotiate new international law on fully autonomous weapons. Outlining its position to the Guardian newspaper, the Foreign and Commonwealth Office said: "At present, we do not see the need for a prohibition on the use of LAWS, as international humanitarian law already provides sufficient regulation for this area."[173]

At this point in time the government evidently wishes to keep its options open. Some suggest the government does not want to create barriers which might hinder underlying research into emerging technology such as artificial intelligence and robotics, where there are dual use applications. However, plenty of technologies, such as encryption, or in the area of nuclear, biological and chemical science, can be used for civil or military purposes and are controlled without stifling underlying research. The government's stance unfortunately means that the UK has missed an opportunity to engage with debate on the ethical, human rights and humanitarian challenges posed by autonomous weapons systems, and play a role in developing standards that would prevent their inappropriate development and use.

The Joint Doctrine Publication also states that "Current UK policy is that the operation of our weapons will always be under human control as an absolute guarantee of human oversight and authority and of accountability for weapon usage."[174] The key word here is "current." Government policy can, and does, change regularly depending upon which party is in power and the current political and international context. Parallels from military history indicate that, despite promising to refrain from using new types of weapon which are considered particularly barbarous, in reality governments will take whatever steps they feel are necessary when faced with the pressures of war. The decisions to release ordnance from the air, from under the ocean, and to use atomic weapons were all at first opposed on ethical grounds, yet eventually became acceptable to war planners. It would be unrealistic to believe that pledges to refrain from using autonomous weapons would fare at all differently.

6.2 Conclusion and recommendations

"The technological capability for autonomous weapon systems that can detect and analyse complex environments, select targets and carry out an attack is likely to be reality one day—even if that day is far in the future. But the decision to weaponise these capabilities is not inevitable. International and national discussions must centre around which applications of these capabilities are acceptable, legal, and desirable when applied to the use of force"
    United Nations Institute for Disarmament Research (UNIDIR).[175]

As a nation which considers itself a responsible and leading member of the international community, the United Kingdom has a duty to use its influence and powers to ensure that the weapons of the future are never used outside the boundaries set by the laws of humanity and the requirements of the public conscience. We therefore make the following recommendations to the government and Parliament.

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173 Owen Bowcott: 'UK opposes international ban on developing 'killer robots''. Guardian, 13 April 2015. https://www.theguardian.com/politics/2015/apr/13/uk-opposes-international-ban-on-developing-killer-robots

174 Ministry of Defence: Development, Concepts and Doctrine Centre: 'Unmanned Aircraft Systems'. Joint Doctrine Publication 030.2, 12 September 2017, op cit. Para 4.14, p42.

175 United Nations Institute for Disarmament Research (UNIDIR): 'Framing Discussions on the Weaponization of Increasingly Autonomous Technologies'. 2014, op cit. P11.

- The UK government should support the development of a legal instrument to prevent the development, acquisition, deployment, and use of fully autonomous weapons and ensure that humans are always in control of lethal force decisions. This should include playing a full role in discussions on autonomous weapons currently under way through the forum of the Convention on Certain Conventional Weapons (CCW), with the aim of mandating negotiations on a new CCW protocol by the end of 2019 at the latest. The UK should make concrete proposals to the CCW in 2019 outlining how such a legal instrument could be drafted.

- In order to help build international confidence for a ban on fully autonomous weapons, the UK government should make an unequivocal statement that it is unacceptable for machines to control, determine, or decide upon the application of force in armed conflict and give a binding political commitment that the UK would never use fully autonomous weapon systems.

- The UK should introduce measures to ensure that human control must be exerted over all attacks in armed conflict, and that this control requires commanders not only to understand the weapons systems that they are using but also the contexts where any force may be applied, at the time that it may be applied.

- The UK's definition of autonomy in relation to weapon systems is clearly out of step with those used by other states and international institutions. In order to participate meaningfully in international discussions on these issues we would urge the government to follow the House of Lords Select Committee on Artificial Intelligence's recommendation that the UK's definition of autonomous weapons should be realigned to be the same, or similar, as that used by the rest of the world.

- To increase transparency, the government should publish an annual report identifying research programmes and budgets funded by the Ministry of Defence, security services, and other government bodies in the autonomous technology and artificial intelligence areas.

- The House of Commons Defence Committee and the Joint Human Rights Committee, working with the Centre for Data Ethics and Innovation, should together investigate the impact of emerging military technologies, including autonomy, artificial intelligence, cyber technology, biotechnology, and nanotechnology. The Committees should press the government to adopt an ethical framework, prepared in consultation with stakeholders and civil society, to ensure that future research complies with the laws of humanity and the requirements of the public conscience.

- The government, through the EPSRC, should fund the Alan Turing Institute (for example) to conduct a wide-ranging study into the use of artificial intelligence to identify early stage indicators of armed conflict. This would be in support of conflict resolution and to promote sustainable security. This funding should be matched to DSTL's research budget for work on artificial intelligence programmes.

- The government should initiate a broader public debate on the ethics and future use of artificial intelligence and autonomous technologies, particularly their military applications.

Appendices

Appendix I Weapons systems currently in service with UK armed forces which show autonomous features

Weapon	Type	Mobility	Homing	Navigation	Target identification	Target selection	Target image discrimination	Persistence	Use of force
Royal Air Force									
MBDA Brimstone	Air-to-ground missile fired from Typhoon and Tornado aircraft.	√	√	√	√		√		
MBDA AIM-132 Advanced Short Range Air-Air Missile (ASRAAM)[176]	Air-to-air missile fired from Typhoon, Tornado, and F35 Lightning aircraft.	√	√		√		√		
MBDA Storm Shadow	Long range air launched cruise missile fired from Typhoon and Tornado aircraft.	√	√	√	√		√		
Lockheed Martin AGM-114 Hellfire	Air-to-ground missile fired from Reaper drone.	√	√						
General Atomics MQ-9 Reaper	Medium-to-high altitude long endurance drone.	√		√				√	
Royal Navy									
Raytheon Phalanx[177]	Defensive close-in weapons system based on 20mm Gatling Gun. Deployed on Type 45 destroyers, HMS Albion, and some Royal Fleet Auxiliary ships. Can also be deployed on land.				√	√			√[178]
MBDA GWS-26 Seawolf[179]	Ship-to-air missile deployed on Type 23 frigates.	√	√		√	√			
EUROPAAMS Principal Anti Air Missile System (Sea Viper)[180]	Ship-based anti-missile system firing MBDA / Thales Aster missile. Deployed on Type 45 destroyers.		√	√	√	√			
Raytheon Tomahawk Block IV UGM-109E[181]	Submarine launched land attack cruise missile. Deployed on Astute and Trafalgar class submarines.	√	√	√	√		√	√	
Lockheed Martin Trident D5 UGM-133	Undersea long-range missile system. Deployed on Vanguard class submarines.	√	√	√					

176 Royal Air Force: 'AIM-132 ASRAAM' https://www.raf.mod.uk/equipment/asraam.cfm

177 Raytheon UK: 'Phalanx Close-in Weapon System'. http://www.raytheon.co.uk/capabilities/products/phalanx/

178 Phalanx and Raytheon have the ability to make autonomous decisions on the use of force with a human is 'in the loop'.

179 NavWeaps.com: 'Sea Wolf GWS-25, GWS-26, and GWS-27'. 20 November 2006. http://www.navweaps.com/Weapons/WMBR_Sea_Wolf.php

180 Think Defence: 'Sea Viper (ASTER)'. http://www.thinkdefence.co.uk/uk-complex-weapons/sea-viper-aster/

181 'RGM/UGM-109 Tomahawk'. Forecast International Aeroweb. http://www.fi-aeroweb.com/Defense/Tomahawk.html

Weapon	Type	Mobility	Homing	Navigation	Target identification	Target selection	Target image discrimination	Persistence	Use of force
BAE Systems Spearfish	Anti ship and submarine torpedo. Deployed on Astute, Trafalgar, and Vanguard class submarines.	√	√		√				
BAE Systems Stingray Mod 1	Anti submarine torpedo. Deployed on Type 23 frigates and Wildcat and Merlin helicopters.	√	√		√				
Army									
MBDA Rapier 2000 [182]	Ground-to-air missile air defence system.		√	√	√				√[178]
Foster-Miller Talon[183]	Remote controlled unmanned ground vehicle used for bomb disposal. Can be armed.	√						√	
UAV Tactical Systems Watchkeeper WK450[184]	Medium altitude long endurance drone. Unarmed and intended for ISTAR missions.	√		√				√	

Adapted from Heather Roff and Richard Moyes (2016)[185]. All information from this source unless otherwise annotated.

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182 Army Technology: 'JERNAS / Rapier FSC Air Defence System'. http://www.army-technology.com/projects/jernas/

183 'TALON Tracked Military Robot'. Army Technology. http://www.army-technology.com/projects/talon-tracked-military-robot/

184 Although not an armed weapon system, Watchkeeper can be used to "cue military action" and "mark targets", according to its manufacturers. 'Watchkeeper'. Thales Group webpage. https://www.thalesgroup.com/en/global/activities/defence/unmanned-aerial-vehicles-systems/tactical-uav#performance.

185 Heather Roff and Richard Moyes: 'Project: Artificial Intelligence, Autonomous Weapons, and Meaningful Human Control', op cit.

Appendix II Research into autonomous and drone technology in British universities.

In order to obtain an indication of the nature and extent of work relating to the development of autonomous systems and drones in UK-universities, Drone Wars UK undertook a short survey over the period November 2017 – March 2018 based on requests made under the terms of the Freedom of Information Act 2000. We approached a sample of twelve universities with departments that were considered likely to be undertaking research in this field and submitted the following request:

> I should be grateful if you would provide me with a list of all research projects funded by:
> – The Ministry of Defence, including the Defence Science and Technology Laboratory (DSTL);
> – BAE Systems plc;
> – Thales Group;
> – and / or QinetiQ Group plc
> conducted at [University name] in the following departments over the period 1 January 2015 to the present day [November 2017]:
> [Department names]

Relevant results are summarised in Table 1 below (projects clearly outside the scope of this study are omitted). The survey does not claim to be an authoritative investigation, and some of the projects listed may not be related to autonomous systems or drones, and it is highly likely that other projects are ongoing which were not captured. Nevertheless, the survey clearly showed that a number of universities are involved in research into military-sponsored work on autonomous systems, notably focusing on sensor development, image processing, and the control and performance of autonomous systems.

Table 1: UK university departments undertaking research into autonomous systems and drones.

University and departments	Project title	Funding source	Funding awarded
Cranfield University[186]			
Unmanned autonomous systems laboratory. UAV laboratory. Centre for autonomous and cyber-physical systems.	Study on future uninhabited air dominance capabilities.	BAE Systems	£15,000
	Autonomous Systems Underpinning Research (ASUR) Project: Novel power generation and energy management using hydrogen pellet system.	BAE Systems	£42,000
	PhD Research: Bioinspired omnidirectional vision: integrated approach.	MoD / DSTL	£92,727
Imperial College			
Institute for Security Science and Technology. Electrical and Electronic Engineering Department.	Enabling Technologies for "UAV Array" Signal Processing.	DSTL	£72,939
	Phase 2: "Manifold Extender" for "UAV Array" Signal Processing.	DSTL	£154,760
	Information withheld under section 26(1)(b) of the FOIA 2000 (Defence exemption).	DSTL	£91,417
	Information withheld under section 26(1)(b) of the FOIA 2000 (Defence exemption).	DSTL	£355,512
	Information withheld under section 26(1)(b) of the FOIA 2000 (Defence exemption).	DSTL	£685,299
	Sky Swarm Feasibility Assessment.	DSTL	£37,692

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University and departments	Project title	Funding source	Funding awarded
Loughborough University			
Loughborough University Centre for Autonomous Systems.	Terminal Region Operation of Unmanned Aircraft Systems	BAE Systems	£25,500
	Maintaining Network Connectivity and Performance Using UAVs for Multi-Layer ISR System.	DSTL via BAE Systems	£39,901
	Gust alleviation for mini UAVs using disturbance rejection flight control.	DSTL via BAE Systems	£39,783
University College London			
Computer Science Department.	Theoretic approaches to minimal sensing for maximal detection.	Not stated	£131,813
	Scalable video super-resolution and fusion.	Not stated	£85,000
	DSTL ASUR Unmanned sensor multilayer control.	Not stated	£11,000
	Machine learning aided electromagnetic imaging.	Not stated	£88,980
University of Bristol			
Department of Aerospace Engineering.	Studentship: EPSRC Centre for Doctoral Training in Future Autonomous and Robotic Systems – FARSCOPE	BAE Systems	Not stated
	The university confirmed that it has also worked with MoD and DSTL but claimed that details of these projects are exempt from disclosure.		
University of Cambridge			
Department of Engineering.	Maritime Imaging for the Identification of Vessels and Activities through Turbulence.	DSTL	£121,483
		DSTL	£90,792
	Research PhD: Understanding and Enhancing Cognition and Performance: Attention-Aware Multi Display Environments that Visualise Changes on Unattended Displays	BAE Systems	£248,675
	Evolutionary Human-Machine Interfaces		
University of Edinburgh			
Centre for Robotics.	No funding for such work received over this period.		
University of Liverpool			
Liverpool School of Engineering (including the Centre for Autonomous Systems Technology).	Type 26 Global Combat Ship - Airwake Analysis and Modelling Study.	BAE Systems	£346,000
	Ship-Board Launch and Recovery of an Unmanned Autonomous Air System: Surviving the Ship Air Wake.	BAE Systems	£120,300
	A Toolkit to Measure Accuracy and Decision Confidence in Human-Machine Interaction.	DSTL	£132,621
University of Oxford			
Department of Engineering Science.	Still awaiting full information.		
University of Sheffield			
Department of Automatic Control and Systems Engineering.	No funding for such work received over this period. The university confirmed that it has received funding from MoD, BAE Systems, Qinetiq, and Thales for work in other departments[187].		
University of Southampton			
Autonomous Systems University Strategic Research Group.	No funding for such work received over this period		
University of Warwick			
Department of Computer Science.	No funding for such work received over this period.		

187 Although the University of Sheffield claimed that the Department of Automatic Control and Systems Engineering did not receive funding within the scope of our request, the University's website states that the department has worked with Thales on the development of intelligent autonomous surface vehicles which can cope with rough weather conditions. 'University of Sheffield: 'Department of Automatic Control and Systems Engineering': https://www.sheffield.ac.uk/acse/research/groups/asrg/collaborators

Separately, a Freedom of Information Act request to DSTL requesting information on contractors working on projects in DSTL's 'Command, Control, Communications, Communications & Intelligence & Big Data (C4I)' research programme has revealed that a number of universities are also involved in research in this field[188]. The universities involved are:

- Birkbeck, University of London
- Bournemouth University
- Cranfield University
- Durham University
- Imperial College
- Middlesex University
- Oxford University Innovation Ltd

- University College London
- University of Edinburgh
- University of Kent
- University of Liverpool
- University of Sheffield
- University of Southampton
- University of Surrey

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Glossary

3D	3 Dimensional
ACER	Autonomous Control Exploitation and Realisation
AI	Artificial Intelligence
ARGUS-IS	Autonomous Real-Time Ground Ubiquitous Surveillance Imaging System
ASTRAEA	Autonomous Systems Technology Related Airborne Evaluation & Assessment
ASUR	Autonomous Systems Underpinning Research
ATOLS	Automatic Take Off and Landing System
AWCFT	Algorithmic Warfare Cross-Functional Team
C2	Command and Control
C4I	Command, Control, Communications, Computers and Intelligence
CDE	Collateral Damage Estimate
CDEM	Collateral Damage Estimate Methodology
CIA	Central Intelligence Agency
CCW	Convention on Certain Conventional Weapons
DARPA	Defense Advanced Research Projects Agency
DASA	Defence and Security Accelerator
DERA	Defence Evaluation and Research Agency
DoD	Department of Defense
DSEI	Defence and Security Equipment International
DSTL	Defence Science and Technology Laboratory
EA FOCUS	Enhanced Awareness and Forward Operating Capability for Unmanned Air Systems
ENIAC	Electronic Numerical Integrator And Computer
EPSRC	Engineering and Physical Sciences Research Council
FAST-CD	Fast Assessment Strike Tool – Collateral Damage
FLAVIIR	Flapless Air Vehicle Integrated Industrial Research
GCHQ	Government Communications Headquarters
GPS	Global Positioning System
HM	Her Majesty's
IARPA	Intelligence Advanced Research Projects Agency
IAS	Intelligent Adaptive Software
ISIS	Islamic State of Iraq and Syria
ISTAR	Intelligence, Surveillance, Target Acquisition and Reconnaissance
ISR	Intelligence, Surveillance, and Reconnaissance
LAWS	Lethal Autonomous Weapons System
MAST	Maritime Autonomy Surface Testbed
MoD	Ministry of Defence
NATO	North Atlantic Treaty Organisation

PED	Processing, Exploitation, and Dissemination
QCDE	Quick Collateral Damage Estimation
QCDE	Quick Collateral Damage Estimation
RAF	Royal Air Force
RAG	Red Amber Green
SAX	Special Activity Exploitation
SIPRI	Stockholm International Peace Research Institute
UK	United Kingdom
UAS	Unmanned Aircraft System
UAS CDC	Unmanned Air Systems Capability Development Centre
UAV	Unmanned Aerial Vehicle
US	United States
USAF	United States Air Force
USS	United States Ship
UxV	Unmanned [x] Vehicle [operating in either the air, sea, or on land]
VISX	Video, Image, and Spectral Exploitation
VTOL	Vertical Take Off and Landing
WUASE	Wales Unmanned Aircraft Systems Environment

Acknowledgements