MAPPING THE INNOVATION ECOSYSTEM DRIVING THE ADVANCE OF AUTONOMY IN WEAPON SYSTEMS

VINCENT BOULANIN

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STOCKHOLM INTERNATIONAL
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Abbreviations

3-D	Three-dimensional
AGI	Artificial general intelligence
AI	Artificial intelligence
CCW	Convention on Certain Conventional Weapons
CODE	Collaborative Operations in Denied Environment
CwC	Communicating with Computers
DARPA	Defense Advanced Research Project Agency
EU	European Union
GPS	Global Positioning System
ICT	Information and communication technology
IMU	Inertial measurement unit
LAWS	Lethal autonomous weapon systems
LDUUV	Large Displacement Unmanned Undersea Vehicle
LOCUS	Low-Cost UAV Swarming Technology
LRASM	Long range anti-ship missile
MASI	Microsoft Academic Search Index
MIT	Massachusetts Institute of Technology
NGO	Non-governmental organization
R&D	Research and development
TRACE	Target Recognition and Adaptation in Contested Environments
UAV	Unmanned aerial vehicle
UGS	Unmanned ground system
UMS	Unmanned maritime system
USS	Unmanned surface system
USV	Unmanned surface vehicle
UUS	Unmanned underwater system
WIPO	World Intellectual Property Organization
XAI	Explainable Artificial Intelligence

1. Introduction

Since 2013 the governance of lethal autonomous weapon systems (LAWS) has been discussed internationally under the framework of the 1980 United Nations Convention on Certain Conventional Weapons (CCW).[1] Thus far, the discussion has remained at the informal level. Three informal meetings of experts (held in 2014, 2015 and 2016) have been convened under the auspices of the CCW to discuss questions related to emerging technologies in the area of LAWS. The mandate of these meetings gave no indication of what the outcome of the discussion should be beyond deepening the understanding of LAWS and how such weapon systems may be created. Nonetheless, the question of whether the CCW should take formal action and adopt a new protocol was included in the discussions, notably thanks to the advocacy work of the Campaign to Stop Killer Robots—a non-governmental organization (NGO) coalition that is calling on states parties to negotiate and adopt a pre-emptive ban on the development, production and use of LAWS.[2] Only a few states have expressed their readiness to discuss that possibility so far, the majority being still in the process of understanding the issues at stake.

Several delegations have, however, already indicated that they have concerns as to the impact that a new protocol on LAWS could have on innovation, particularly in the civilian sphere, since, arguably, much of the technology on which LAWS might be based could be dual use.[3] The empirical foundations of these concerns are the focus of this working paper.

The aim of this working paper is to help delegates and the interested public to better understand the 'innovation ecosystem' that is driving the development of autonomy in weapon systems. The paper maps out where relevant innovations are taking place from three different perspectives: (*a*) a science and technology perspective (the field of research and development, R&D), (*b*) a geographical perspective (the location of key R&D institutions), and (*c*) a sector perspective (whether innovation is driven by civil or military research). It should be emphasized that the purpose of this paper is neither to advocate, nor argue against, the development of a new protocol, rather the purpose is to set an unbiased baseline for future discussions on the feasibility and impact of a protocol dedicated to LAWS.

The next section (section 2) provides a brief background on innovation and discusses the challenges associated with mapping innovation in machine autonomy. Sections 3, 4 and 5 discuss relevant developments within the academia, the governmental military research agencies and the private sector respectively. The concluding section (section 6) summarizes the key findings and presents some takeaways for future CCW discussions.

[1] Convention on Prohibitions or Restrictions on the Use of Certain Conventional Weapons which may be Deemed to be Excessively Injurious or to have Indiscriminate Effects (CCW Convention, or 'Inhumane Weapons' Convention), with Protocols I, II and III, opened for signature 10 Apr. 1981, entered into force 2 Dec. 1983, <http://treaties.un.org/Pages/CTCTreaties.aspx?id=26>.

[2] Bolivia, Cuba, Ecuador, Egypt, Ghana, the Holy See, Pakistan, Palestine and Zimbabwe expressed clear support for a ban on LAWS. Croatia, Ireland and Sri Lanka are open to considering a ban.

[3] The concept of 'innovation' refers both to the process, and the result of, technological development that leads to the creation of new methods, ideas or products.

2. Background: what is innovation and why is it difficult to track in the context of machine autonomy?

Innovation in the context of autonomy is a complex issue. Thus, it is useful as a first step to clarify some of the essentials of the R&D process through which new technologies, notably military technologies, are generally created. This section also reviews the methodological challenges associated with mapping innovation in the area of machine autonomy.

I. The essentials of innovation

Types of research and development efforts

Innovation typically results from formal R&D efforts, which can be divided into three categories: basic research, applied research and experimental development. These three categories can be summarized as follows:

1. *Basic research* is about advancing the state of science and knowledge at the fundamental level, through theoretical or experimental inquiry.
2. *Applied research* is about researching new methods and techniques to address concrete socio-technical problems. In contrast to basic research, applied research pursues a concrete objective.
3. *Experimental development* builds on the findings of basic research and applied research to improve existing, or develop new, technology—be it new material, products, systems or services.

This last phase is crucial as far as the development of marketable technologies is concerned—be they civilian or military technologies. It is during this phase that new methods, ideas or products possibly take their final shape. Thus, from a regulatory point of view, it is the phase that is the most important to monitor and control. However, the importance of basic and applied research should not be underestimated, as major technological breakthroughs cannot happen without basic and applied research.

The innovation ecosystem: key players and their relationship

R&D efforts leading to innovation can be conducted within any of the following three types of institutions: university research laboratories, government civilian and military research laboratories, and private sector laboratories.

University laboratories

University laboratories are usually more concerned with research than development. Their primary role is to advance science and technology through fundamental research. In contrast to the research labs of private companies, their research efforts do not necessarily need to translate into innovations that may be monetized. Nonetheless, universities in many countries are increasingly involved in various forms of collaboration with industry to advance technologies with potentially marketable applications—including military applications. In addition, it is not uncommon that university labs receive military funding to work on R&D projects that are of interest to the armed forces. Their involvement, however, rarely goes beyond the applied research phase. Some universities have internal rules that specifically limit their ability to participate in weapon development. The Massachusetts Institute of Technology

(MIT), for instance, allows its researchers to receive military funding only for basic and applied research. Stanford University has a policy stating that research professors may hire students of any nationality to work on research projects. Since there are likely to be additional nationality restrictions on persons working on sensitive military R&D projects, research teams from Stanford University may be prevented from participating if those teams include students from certain states.

The restrictions on research conducted by universities are one of the reasons why academic researchers sometimes establish businesses to run alongside their academic activities. By forming a private company, researchers can receive further funding for experimental development or directly exploit commercially the findings of their academic research. One of the most notable examples is Boston Dynamics, which was founded in 1992 by Marc Raibert as a spin-off of the MIT Leg-Lab—a research group then headed by Raibert focused on the development of self-balancing robots with legs. Since then, Boston Dynamics has received multiple R&D contracts with the United States' Department of Defense, which led to the development of advanced and widely discussed prototypes of four- and two-legged robots.

Thus, the contribution of university labs to innovation is not limited to delivering research that tackles generic socio-technical problems, such labs also serve as incubators for talents and ideas that can then grow in the private sector.

Governmental civilian and military research laboratories

Governmental civilian and military research labs focus usually on applied research, but in some cases they can also conduct or support basic research and experimental development projects. The types of applied research that they commonly conduct can be subdivided into two categories: strategic applied research and specific applied research. Strategic applied research projects have a purely prospective nature and are meant to explore technological developments over very long time frames (e.g. 10–50 years). Specific applied research projects are directed towards near-time and specific innovation. Typically, they test and demonstrate the usefulness of new technologies in light of short-run requirements (e.g. 5–10 years).

Historically, governmental research institutions, notably military research labs, have played a key role in the development of game-changing technology, for the simple reason that they were able to invest in R&D projects that neither the academia nor private companies were willing or able to support or articulate alone. The USA's Defense Advanced Research Project Agency (DARPA) is perhaps the best known of these research institutions. DARPA has long been a leader of innovation in many areas of science and technology, including artificial intelligence (AI) and robotics—the two fields of science and technology that are essential to the development of autonomy (see section 3). A number of DARPA projects have not only resulted in entirely new techniques or ways of doing things, but have also resulted in disruptive innovations (i.e. innovations that create new markets or disrupt existing markets) such as stealth technology, the Global Positioning System (GPS) and the Internet. One of DARPA's distinguishing features is that, in contrast to many other governmental research institutions, it is not itself engaged in R&D work. It designs, funds and oversees projects, but it 'outsources' the actual research process to academic institutions and private companies. This model has been particularly effective at facilitating the deployment of innovation to the marketplace. A number of countries, including Russia, Japan and—more recently—China, have attempted to reproduce the DARPA model.[1]

[1] Xin, H., 'China to create its own DARPA', *Science Mag*, 11 Mar. 2016; Beckhusen, R., 'Putin wants a DARPA of his own', *Wired*, 25 June 2012; and Reuters, 'Japan to tap technology for military use, in another step away from pacificism', *Financial Express*, 14 Nov. 2013.

Private sector laboratories

Private sector laboratories may conduct all types of R&D efforts, but their focus is mostly on the development part of R&D. When they conduct basic and applied research, it is usually with the intention of developing marketable products and services. Here, it is worth underlining that there are notable differences in the ways in which commercial companies and defence companies research and develop new technologies.[2] These differences generally derive from the fact that defence companies, at least companies that are specialized in arms production, and civilian companies operate in fundamentally different market conditions. Civilian companies have to invest heavily in R&D to remain competitive. Innovation allows them to attract customers and gain or retain market share. Defence companies, on the other hand, operate in a market characterized by monopsony (i.e. a market where there is only one customer: the state).[3] Their R&D efforts are therefore largely determined by the evolution of government demand. They need to adapt their research agenda to priorities that are set, and volume resources made available, by the military. In general, they do not invest in the development of new military products or services without the guarantee that they will be able to sell them.[4] This is not to say that some defence companies do not make significant self-funded R&D efforts, but these are usually of a smaller scale than those of their commercial counterparts, and they usually reflect a conservative approach towards developing new technology.[5] An appreciation of these differences is essential to an understanding of why defence companies may appear less proactive than their commercial counterparts in the area of machine autonomy—something that will be discussed further in section 5.

The innovation ecosystem

Together, university labs, governmental research agencies and private sector labs form what is often referred to as an 'innovation ecosystem' (see box 1). A number of economic studies have shown that a state's ability to deliver high-quality innovation is concomitant with its ability to create or facilitate interaction between these different institutions, be that in terms of exchange of fundamental knowledge, personnel or funding.[6]

The relationship between civilian and military innovation

When discussing the relationship between civilian and military innovation it is important to note that 'innovation' has two meanings: it may refer both to the process of, and the result of, technological development.

Innovation that results from military R&D (i.e. R&D that is funded or conducted by military research institutions) can find applications in the civilian sphere and vice versa.[7] What determines whether the result of innovation is both a military and

[2] Tama, J., *There's No App for That: Disrupting the Military–Industrial Complex* (Brookings: Washington, DC, 2015), p. 27.

[3] It is very rare for defence companies to develop new and capital-intensive projects for governments other than the one in the country in which they primarily operate.

[4] Defence companies usually make states cover most R&D costs associated with the production of new military technologies. Sköns, E., *The Globalization of the Arms Industry*, Phd Dissertation (Bradford University: Bradford, 2009), p. 45.

[5] According to the research firm Capital Alpha Partners, the combined R&D budgets of 5 of the largest US defence contractors (about $4 billion) amounts to less than half of what companies such as Microsoft or Toyota spend on R&D in a single year. Lynn III, W. J., 'The end of the military–industrial complex', *Foreign Affairs*, Nov./Dec. 2014.

[6] Wadhwa, V., 'Silicon Valley can't be copied', *MIT Technology Review*, 3 July 2013; and Dutta, S., Lanvin, B. and Wunsch-Vincent, S. (eds), *Global Innovation Index 2016* (Cornel University, INSEAD and WIPO: Icatha, Fontainbleau and Geneva, 2016).

[7] There is a large volume of literature discussing, in depth, the relationship between civilian, military and dual-use innovation. Most of this literature was published around the end of the cold war, when a number of experts explored

Box 1. Innovation ecosystem

Academia, government civil and military research agencies and the private sector interact with each other in different ways.

Academia delivers basic knowledge, ideas and trained personnel that civil and military research agencies and private companies can use to innovate.

Government civil and military research agencies conduct civil, military and dual-use research of interest and provide funding and research ideas to academia and the private sector.

The private sector develops research ideas into marketable products. It can also directly fund academic research.

civilian technology is its end use. Technologies that can be developed and used both for military purposes and for civilian purposes are colloquially referred to as dual-use technologies.[8]

In many areas of the science of technology there is nothing fundamental at the basic and applied research level to determine whether a certain area is civil or defence oriented.[9] This is particularly the case for most enabling technology areas such as electronics, computer programming and advanced material. The divergence between civilian and military innovation generally emerges during the development stage of the R&D cycle, as it is during that stage that the end-user requirements are factored in. One well-established difference between the military and the civilian sectors is the fact that the military end user often places greater emphasis on performance, survivability and reliability of the technology than on aesthetics and cost, while the civilian end user might focus on cost-limitation, user-friendliness or aesthetics.[10] This is especially true of final systems such as vehicles or information and communication technology (ICT).

Thus, contemporary military technologies, even weapon systems, rarely originate only from 'pure' military research efforts; rather they result from developments in both civilian and military R&D that have synthesized in military applications.[11] This trend is not new, but has been increasing rapidly over the past 20 years thanks to the growing role played by electronics and ICT in the design of military systems. Electronics and ICT are prime examples of dual-use technology, whose development has been chiefly driven by the commercial sector for decades.

The key takeaway from this brief background introduction is that to understand the dynamic of innovation in military technology, it is useful to consider the entire R&D cycle, not just the phase of experimental development that primarily takes place within the industry. The remaining sections of this paper aim to map out and analyse the relevant R&D efforts carried out within academia, governmental research agencies and the private sector. Before continuing with this mapping exercise, it is first necessary to discuss the extent to which it is actually feasible to map innovation in the context of autonomy.

the possibility of diverting military resources to the civilian sector. Since then, a relatively limited number of academic studies have been published on the topic. Carter, A. et al., *Beyond Spin-Off: Military and Commercial Technologies in a Changing World* (Harvard Business School: Boston, MA, 1992).

[8] Cowan, R. and Foray, D., 'Quandaries in the economics of dual technologies and spill-overs from military to civilian research and development', *Research Policy*, vol. 24, no. 6 (1995), p. 851.

[9] Davis, I., *Military R&D in Europe, Collaboration Without Control?* (Oxford Research Group: Oxford, 1992), p. 11.

[10] Kaldor, M., *The Baroque Arsenal* (Abacus: London, 1991); and Dunne, P., 'Defense industrial base', eds K. Hartley and T. Sandler, *Handbook of Defense Economics*, vol. 1 (Elsevier: Amsterdam, 1995).

[11] Davis (note 9), p. 11.

Box 2. Anatomy of autonomy

From a technical perspective, autonomy entails an ability to transform data perceived from the environment into purposeful plans of action.

At a fundamental level, it is always enabled by the same types of technology:

1. *Sensors* that allow the system to gather data about the world.
2. *A suite of computer hardware and software* that allows the system to interpret data from the sensor and transform it into plans and actions. The three most important technologies in this regard are computer chips, sensing software and control software that together form the 'brain' of the system.
3. *Communication technology and human–machine interfaces* that permit, when appropriate, the system to interact with other agents, whether they are machines or humans.
4. *Actuators and end-effectors*, and *power sources* that allow the system to execute the actions in its operating environment.

These different components form the underlying architecture of autonomy. The actual characteristics of these underlying technologies will be different depending on the nature of the task and the operating environment.

II. Innovation and autonomy

Mapping innovation in machine autonomy poses a significant challenge from a methodological standpoint. Autonomy has no established definition. It is neither a specific technology area with well-defined boundaries nor a dedicated academic discipline nor a distinct market sector.[12] Autonomy is not even technology per se; rather it is a property that can be attached to very different types of technology.

Moreover, while machine autonomy is always made possible by the integration of the same types of enabling technologies (see box 2), the characteristics of these enabling technologies vary significantly depending on their relevance to the applications and capabilities of interest. This means that, even in the context of military weapon systems, the underlying technological architecture may vary within and between systems, depending for instance on the nature of the tasks that are executed, the weapon system's mission and the nature of the operating environment. Therefore, it is not feasible to capture and discuss in a single study all the technological developments that may be relevant to advances of autonomy in weapon systems.[13]

To make the scope of this study more manageable, an emphasis has been placed on the development software technologies that allow autonomous weapon systems or subsystems to feature greater perception and decision-making capabilities. Some developments related to hardware components such as sensor technology and computer processor technology will be discussed at the margins of this paper since they are in some cases directly relevant for the performance of software technologies.[14]

[12] 'Autonomy' is defined here as the ability of a technology to execute a task, or tasks, without human input, using interaction of computer programming with the environment. This definition is based on one previously proposed by Andrew Williams. Williams, A., 'Defining autonomy in systems: challenges and solutions', eds A. Williams and P. Scharre, *Autonomous Systems: Issues for Defence Policymakers* (NATO Headquarters Allied Command: Norfolk, VA, 2015).

[13] US Department of Defense (DOD), Office of Technical Intelligence, Office of the Assistant Secretary of Defense for Research and Engineering, *Technical Assessment: Autonomy* (DOD: Washington, DC, Feb. 2015), p. 24.

[14] For a more detailed discussion on what autonomy is and how it is created see Boulanin, V., *Mapping the Development of Autonomy in Weapon Systems: A Primer on Autonomy*, SIPRI Working Paper (SIPRI: Stockholm, Dec. 2016).

3. Academia

This section maps out the networks of research disciplines and research issues that are involved directly (or in some cases indirectly) in the development of autonomous capabilities in weapon systems. It also provides an overview of the global academic landscape in this area and identifies the locations of the world's leading academic research institutions in this field.

I. Artificial intelligence and robotics

At the basic science and technology level, advances in machine autonomy derive primarily from research efforts in two disciplines: AI and robotics.

Artificial intelligence

According to John McCarthy, who coined the concept in 1955, AI can be broadly defined as the 'science and engineering of making intelligent machines'.[1]

As an academic discipline, AI mainly falls within computer science. The centre of gravity of AI research is difficult to delineate satisfactorily, partly because the concept of AI means different things to different people, and partly because its subject matter, intelligence, is difficult to define. Historically, core AI research has focused on problem solving through logic and reasoning. Many researchers and engineers continue to think of AI in those terms. Others see it as an umbrella term that covers all the research issues that are associated with making machines do tasks that humans label as intelligent (e.g. observing the world through vision, learning and natural language processing).[2]

One distinction worth mentioning here is the difference between specialized AI (weak AI) and artificial general intelligence (AGI) (strong AI) (see box 3). Most current research relates to the development of specialized/weak AI. AGI has always fascinated AI researchers, but it remains a fundamental technical challenge. There are, in fact, strong disagreements as to whether it would even be possible to design AGI computer programs.[3]

Robotics

Robotics is a field of science and engineering that is dedicated to the development of robots (i.e. computer-enabled machines that can sense and purposefully act on or in their environment).[4] As an academic discipline, robotics is at the crossroads between mechanical engineering, electrical engineering and computer science.

Broadly speaking, R&D in robotics falls into one of two generic categories. The first category consists of R&D efforts that mainly focus on development and integration of the hardware parts of robots, notably the actuators and the end-effectors.[5] These

[1] Dale, R. 'An introduction to Artificial Intelligence', A. Din (ed.), *Arms and Artificial Intelligence* (SIPRI/Oxford University Press, Oxford, 1987), p. 33.

[2] See e.g. Russell, S. and Norvig, P., *Artificial Intelligence: A Modern Approach*, 3rd edn (Pearson Education: Harlow, 2014).

[3] Dileep, G., 'Killer robots? Superintelligence? Let's not get ahead of ourselves', *Washington Post*, 4 Nov. 2015; and Adams, T., 'AI: we are like small children playing with a bomb', *The Guardian*, 12 June 2016.

[4] Winfield, A., *Robotics: A Very Short Introduction* (Oxford University Press: Oxford, 2012); and 'Why is it so difficult to define "robot?"', Robohub, 29 Apr. 2016, <http://robohub.org/robohub-roundtable-why-is-it-so-difficult-to-define-robot/>.

[5] End-effectors are the physical devices that assert physical force on the environment: wheels, legs and wings for locomotion, as well as grippers and, of course, weapons. Actuators are the 'muscles' that enable the end-effectors to exert force and include things such as electric motors, hydraulic cylinders and pneumatic cylinders.

Box 3. Artificial general intelligence vs specialized artificial intelligence

In the artificial intelligence (AI) community, the concepts of *artificial general intelligence* (AGI) and *strong AI* refer to a general purpose AI that would be as intelligent as, or even more intelligent than, humans. A system with AGI would be able to make sense of the world itself and develop its own meaning for the environment it encounters. AGI does not currently exist and remains for now in the realm of science fiction. Currently, *specialized AI* or *weak AI* is the only type of AI technology in existence. A system with specialized AI can make complex decisions based on reasoning and past sets of data, but needs to be trained and pre-programmed for specific applications. Such systems have no capability to think beyond the limits of their programming.

efforts aim to improve, for instance, the agility, endurance, flexibility, hardiness, size or velocity of robots. This category includes specific subfields of research such as soft-robotics (which covers the construction of robots that are made from soft and transformable material) or nano-robotics (which covers robots that range in size from 0.1–10 micrometres and are constructed of nanoscale or molecular components).

R&D efforts in the second category mainly focus on the development of the hardware and software parts that control the robot's behaviour. These can be further divided into two subcategories: (*a*) those that seek to improve the ability of humans to remotely control the behaviour of the robot (e.g. through haptic control), and (*b*) those that seek to develop robots capable of governing their own behaviour (i.e. self-governance). The latter subcategory is a fundamental part of research in the area of machine autonomy and is where the robotics and AI disciplines directly overlap. The terms 'AI robotics', 'cognitive robotics' or 'autonomous robots research' are sometimes used in, or to refer to, this area of robotics research.[6] Basic research areas that are shared by the AI and robotics research community and that are of key importance to the development of autonomy include the following:

1. *Computer vision*: the development of computers and robots capable of acquiring, processing, analysing and understanding visual data.

2. *Natural language processing*: the development of computers and robots capable of acquiring, processing, analysing and generating human language.

3. *Machine learning*: the development of computers and robots capable of adapting to their environment and improving performance based on past experiences and training, rather than a pre-programmed model of the world.

4. *Search and planning*: the development of computers and robots capable of developing or adapting plans of action to achieve desired goals.

5. *Optimal control*: the development of computers and robots capable of optimal level decision making to reach a desired goal.

6. *Problem solving*: the development of computers and robots capable of solving well-defined problems (e.g. playing games).

7. *Logical reasoning*: the development of computers and robots capable of reasoning and drawing inferences from a database of facts.

8. *Manipulation*: the development of robotic systems capable of manipulating physical devices in a precise way (e.g. so that the correct level of pressure is applied to an object when grasped).

9. *Human–machine interaction*: the development of improvements to the way in which humans and machines (either computers or robots) work together.

10. *Collaborative intelligence*: the development of several individual machines capable of completing a task collectively (e.g. as a swarm).

[6] Khamassi, M. and Doncieux, S., 'Nouvelles approches en robotique cognitive' [New approaches in cognitive robotics], *Intellectica*, vol. 1 (2016); and Murphy, R., *Introduction to AI Robotics* (MIT Press: Cambridge, MA, 2000).

11. *Validation and verification*: the development of methods to ensure that intelligent systems satisfy certain desired formal properties and meet formal requirements (i.e. that they do not have unwanted behaviours or consequences).

All these research areas constitute separate subfields of academic research. They have dedicated academic conferences, as well as research teams with university labs. It should be noted that members of the research community vary significantly depending on the subfield under consideration. Validation and verification for instance is a topic that is covered by a relatively small community of scholars when compared with topics such as computer vision or manipulation. In the subfield of machine learning—an area that is of growing importance to the development of intelligent systems—academics are being lured away from universities to private companies, many of which have a vested interested in the development of machine learning.[7] Reportedly, the most renowned scholars in machine learning are now primarily affiliated with private companies rather than universities.[8]

The relationship with other academic disciplines at the basic and applied research levels

Academic research in the fields of AI and robotics is essentially an interdisciplinary pursuit. This is particularly notable at the basic and applied research levels, where researchers often attempt to connect with, and learn from, many scientific disciplines, including biology, psychology, linguistics and mathematics.

Biology

Interest in biology derives from the fact that the natural world has been, and continues to be, a central source of inspiration for AI and robotics scholars. In the field of AI, many researchers are seeking to draw upon recent discoveries in neuroscience about the structure and functions of the human brain. AI researchers are particularly interested in exploiting that knowledge to generate advances in machine cognition, notably with regard to learning and decision making.[9] The connection with biology is even more palpable in the field of robotics. The shape and behaviour of robots are often inspired by the shape and behaviour of natural bodies. Iconic examples include the legged robots developed by Boston Dynamics. These were developed based on research on animal locomotion conducted by the company's founder while he was head of the MIT's Leg-Lab.[10] The current development of swarm robotics also builds heavily on biologic research on swarm intelligence in the animal word.[11]

Psychology

The AI and robotics research community works in close cooperation with researchers in psychology. Human psychology and cognition provide important benchmarks for AI and robotics researchers who are modelling the behaviour and cognitive abilities of intelligent computers and robots.

[7] Hernandez, D. and King, R., 'Universities' AI talent poach by tech giants', *Wall Street Journal*, 24 Nov. 2016.

[8] Levy, S., 'How Google is remaking itself as "Machine Learning First Company"', *Backchannel*, 22 June 2016.

[9] Potter, S., 'What can AI get from neuroscience', eds M. Lungarella et al., *Fifty Years of AI* (Springer Verlag: Berlin/ Heidelberg, 2007); van der Velde, F., 'Where artificial intelligence and neuroscience meet: the search for grounded architectures of cognition', *Advances in Artificial Intelligence* (2010), pp. 1–18; and Khamassi and Doncieux (note 6).

[10] Knight, W., 'Robots running this way', *MIT Technology Review*, 3 June 2014.

[11] Tan, T. and Zheng, Z-Y., 'Research advances in swarm robotics', *Defence Technology*, vol. 9, no. 1 (Mar. 2013), pp. 18–39.

Linguistics

The AI and robotics research community's interest in linguistics is driven by two key factors: (*a*) improving the ability of machines to process natural language; and (*b*) gaining an understanding of how language is structured, which could help to unravel some of the more complex aspects of human brain function as communication through language is one of the most complex of all human activities.[12] Basic and applied research in AI and robotics that bridge with linguistics can, for instance, aim to improve knowledge representation and reasoning within computers and robots.

Mathematics

The algorithms that govern intelligent systems are mathematical formalization. Research in the field of applied mathematics is, therefore, fundamental as it provides the most basic tools that AI and robotics researchers use to develop their systems.

II. Leading university laboratories

Currently, there are no worldwide university rankings focusing on both AI and robotics that enable an assessment of the leading university labs in these research areas. The study presented in this working paper, therefore, used a simple indicator to obtain a broad impression of the global academic landscape and the locations of key academic research institutions: the volume of affiliated publications in relevant subject matters. This is certainly an imperfect benchmark, as the number of publications neither reflects the quality nor the impact of the research. Also, it references only papers published in English. Nevertheless, it gives some idea of the scientific productivity of universities.

To this end, the Microsoft Academic Search Index (MASI) has proven to be to a useful tool, as it references research publications (it also includes labs operated by private companies) on a number of key AI-related topics—AI in general, machine learning, human–machine interaction, natural language processing and computer vision—and uses that data to rank the top 10 universities in each of these topic areas. The rankings are listed in Appendix A. Unfortunately, MASI does not provide similar rankings for robotics and autonomous systems. The 20 research institutions that were the most often referenced in MASI's publications database for the period 2000–16, using the keywords 'autonomous systems', 'robotics' and 'mobile robots', are listed in Appendix A.[13]

The key lesson learned from these rankings is that, in each topic area, the academic landscape is largely dominated by US universities, most notably: Carnegie Mellon University, Stanford University, MIT and University of California, Berkeley. Outside of the USA, universities that are the most productive on these topics are based in Western Europe, South Korea and China.

III. Conclusion

Research efforts within academia that could be relevant for the future advance of autonomy in weapon systems are primarily taking place in two overlapping research fields: AI and robotics. These fields have in common the fact that they are interdisciplinary and depend on the progress of science in other disciplines, including biology, linguistics, psychology and mathematics. In other words, the foundations of autonomy

[12] Rosenberg, R., 'Artificial intelligence and linguistics: a brief history of a one-way relationship', *Proceedings of the First Annual Meeting of the Berkeley Linguistics Society* (1975), pp. 379–92.

[13] Microsoft Academic Search Index, accessed 9 Dec. 2016, <https://academic.microsoft.com>.

at the basic science and technology level are very diffuse and difficult to map with accuracy. What could be established by this study, however, was that many of the global leaders in terms of research output in the fields of AI and robotics are based in the USA.

4. Governmental research and development

This section discusses the extent to which relevant R&D efforts are taking place or being supported by governmental or military research agencies. It starts by discussing the extent to which it is feasible, based on open sources, to map the volume of resources and types of R&D projects that the 10 largest arms-producing countries dedicate to autonomy. The second part of the section discusses the issue areas currently covered by governmental research agencies.

I. Assessing R&D efforts of the 10 largest arms-producing countries

For the purpose of this working paper, SIPRI attempted to map R&D efforts of governmental research institutions of what SIPRI's data identifies as the 10 largest arms-producing countries—the USA, the United Kingdom, Russia, France, Italy, Japan, Israel, South Korea, Germany, India and China—based on defence companies' arms sales and level of military expenditure (see table 1).[1] The research found that, with the notable exception of the USA and projects funded by the European Union (EU), it is difficult to obtain information both on the level of financial resources dedicated to R&D in the area of autonomy and on the nature of existing R&D projects that may be directly or indirectly related to autonomy.

Level of R&D funding

There is no reliable data to allow a comparison of the level of government funding in each of these countries dedicated to R&D projects in relevant technology areas. The USA is the only country that releases official financial figures related to military R&D and autonomy ($149 million for fiscal year 2015).[2]

In the absence of specific figures, general data on government-funded military R&D can be informative, as it gives some indication of states' commitment to enhancing national security through qualitative improvements in technology rather than (or in addition to) increasing the quantity of armaments.[3] However, here again, there is a data availability issue, since a number of countries, including Russia, China and Israel, do not report how much they spend on military R&D. Nonetheless, it is remarkable to note that the USA spends more on military R&D than the combined total of the six other arms-producing countries for which data could be found (i.e. the UK, France, Italy, Japan, South Korea and Germany). It dedicates more than half of its R&D budget to military R&D, while an important military power like the UK allocates only 17 per cent to military R&D. Such a high level of investment in military R&D is one of the reasons why the US military has maintained a technological superiority over all other states and has been at the forefront of technological innovation since the end of the cold war.

[1] Based on the share of arms sales of companies listed in the SIPRI Top 100 for 2014. The SIPRI Top 100 lists the world's 100 largest arms-producing companies and military services companies (excluding those based in China). These are ranked by volume of arms sales. While not covered by the SIPRI Top 100 due to the lack of data on companies' arms sales, China is also considered as one of the largest arms-producing countries. SIPRI considers that at least 9 of the 10 major state-owned conglomerates under which the Chinese industry is organized would be listed in the Top 100 if official data was available. Fleurant, A. et al., 'The SIPRI Top 100 arms-producing companies and military service companies, 2014', SIPRI Fact Sheet, Dec. 2015.

[2] Bornstein, J., 'DoD autonomy roadmap: autonomy community of interest', presentation at NDIA 16th Annual Science and Engineering Conference/Defense Tech Exposition, Springfield, VA, 24–26 Mar. 2015.

[3] Hartley, K., 'The arms industry, procurement and industrial base', eds T. Sandler and K. Hartley, *Handbook of Defense Economics: Defense in a Globalized World*, vol. 2 (Elsevier: Amsterdam, 2007).

Table 1. Government research and development (R&D) budgets in the 10 largest arms-producing countries

	Arms production data (SIPRI)	Military expenditure data (SIPRI)	Government budgets on R&D (OECD)		
	Share of arms sales in the SIPRI Top 100 for 2014 (%)	Military expenditure 2014 $ b.	Military R&D 2014 $ b. (constant 2010)	Total R&D $ b. (constant 2010)	Share of military R&D in total R&D (%)
USA	*54.4*	596.0	64.4	126.8	*50.8*
UK	*10.4*	55.5	2.3	13.7	*16.9*
Russia	*10.2*	66.4	. .	19.6	. .
France	*5.6*	50.9	1.1	16.7	*6.6*
Italy	*3.0*	23.8	0.1	10.3	*0.9*
Japan	*2.3*	40.9	1.5	33.3[c]	*4.4*
Israel	*1.9*	16.1	. .	1.6[d]	. .
South Korea	*1.7*	36.4	2.7	20.3	*13.5*
Germany	*1.6*	39.4	1.2	29.9	*3.8*
India	*1.2*	51.3	. .	. .	. .
China	. .[a]	(215.0)[b]	. .	. .	. .

. . = not available or not applicable.

[a] Chinese companies are not covered by the SIPRI Top 100 due to the lack of data on which to make a reasonable estimate of arms sales for most companies. Nonetheless, some information is available on the 10 major state-owned conglomerates under which most of the Chinese arms industry is organized. Based on the overall industry picture and on limited information on individual companies, at least 9 of these 10 companies would almost certainly be in the Top 100 if figures for arms sales were available. Of these, 4 to 6 would probably be in the Top 20, and 2—the aircraft producer AVIC and the land systems producer Norinco—may be in the Top 10.

[b] SIPRI estimate.

[c] Military figure based on underestimated data.

[d] Does not include military R&D.

Source: Fleurant, A. et al., 'The SIPRI Top 100 arms-producing companies and military service companies, 2014, SIPRI Fact Sheet, Dec. 2015; Perlo Freeman, S. et al., 'Trends in military expenditure, 2015', SIPRI Fact Sheet, Apr. 2016; and Organisation for Economic Co-operation and Development (OECD) Statistics Database on Research and Development, <www.oecd.org/sti/rds>.

Ongoing R&D projects

The US Government is the most transparent about the types of R&D projects that it funds—not just with regard to the development of autonomy, but military R&D in general. Basic information about the projects that DARPA and the research labs of each military branch (Navy, Army, Marines, Air Force) implement is often available on the web page of each of these branches. The USA also happens to be the only state that currently has an identifiable and articulated research strategy on autonomy.[4]

Finding detailed information about ongoing projects that are either financed or conducted by military agencies in the other top 10 states has proven much more difficult, since very few of them make information available to the public. Appendix B lists, on a country basis, all ongoing publically funded military research projects that could be identified using open sources. This list is most likely far from being comprehensive. In

[4] Bornstein (note 2). The Defense Science Board of the US Department of Defense (DOD) has also issued 2 authoritative reports on autonomy: DOD, Defense Science Board, *Task Force Report: Role of Autonomy in DoD Systems* (DOD: Washington, DC, 2012), and DOD, Defense Science Board, *Report of the Defense Science Board Summer Study on Autonomy* (DOD: Washington, DC, 2016).

some cases, such as China, France, Israel, Italy and South Korea, no substantial information about relevant research initiatives could be found.

II. Research priorities

Projects for which information was available—as listed in Appendix B—can be classified into five thematic categories based on their key objectives: (*a*) generic AI, (*b*) battlefield intelligence, (*c*) human–machine communication, (*d*) command and control and collaborative autonomy, and (*e*) autonomy in unmanned systems. These will be discussed in turn.

Generic AI

The first category covers fundamental and applied research projects that look at generic problems of AI, such as machine learning, that could support advances in various application areas of AI. One notable example is DARPA's Explainable Artificial Intelligence (XAI) project—a research project that aims to create machine-learning models whereby an AI system would be able to explain its decisions and actions to users.

Battlefield intelligence

The second category covers applied research projects that seek to exploit the potential of AI for battlefield intelligence. The majority are about improving the capabilities of sensing algorithms for autonomous surveillance and targeting. DARPA's TRACE (Target Recognition and Adaptation in Contested Environments) project, for instance, aims to use the most recent machine-learning techniques to improve the performance of automatic target recognition systems.

Human–machine communication

The third category consists primarily of applied projects that aim to enhance the sophistication of natural language processing for a number of applications: voice command and control, translation, and language analysis. A handful of projects are also looking to optimize interaction between humans and autonomous systems, notably to increase human trust in autonomy. Such projects include DARPA's CwC (Communicating with Computers) project, which seeks to render computers capable of symmetric communication with humans.

Command and control and collaborative autonomy

The fourth category includes projects that are involved in developing the command and control architecture for autonomous systems. These are mainly aimed at enabling (*a*) autonomous collaboration between multiple systems, and (*b*) control of these systems by a reduced number of human operators. Here again, the USA's DARPA provides a case in point. The CODE (Collaborative Operations in Denied Environment) project aims to make it possible for a group of unmanned aerial systems (also known as unmanned aerial vehicles, UAVs) to work together under one person's supervisory control:

> The unmanned vehicles would continuously evaluate their own states and environments and present recommendations for coordinated … [UAV] actions to a mission supervisor, who would approve or disapprove such team actions and direct any mission changes. Using collaborative autonomy,

CODE-enabled unmanned aircraft would find targets and engage them as appropriate under established rules of engagement, leverage nearby CODE-equipped systems with minimal supervision, and adapt to dynamic situations such as attrition of friendly forces or the emergence of unanticipated threats.[5]

Autonomy in unmanned systems

The last category consists of projects that aim in various ways to develop autonomous capacities on-board unmanned systems: UAVs, unmanned ground systems (UGSs), unmanned surface systems (USSs) and unmanned underwater systems (UUSs). The US Office of Naval Research is working on two notable examples of these types of projects: (*a*) the LOCUS (Low-Cost UAV Swarming Technology) project, which aims to develop swarms of low-cost UAVs that could be used to overwhelm enemy automatic air defence systems; and (*b*) the LDUUV (Large Displacement Unmanned Undersea Vehicle) project, which aims to develop a UUS that could conduct long (over 70 days) intelligence, surveillance and reconnaissance missions.[6]

III. Conclusion

Generally speaking, it remains difficult to find open-source information on R&D projects that governmental military research labs conduct themselves or support the academia or industry to conduct. R&D projects for which information is available range from basic research projects that are intended to improve the design of AI at the most fundamental level to experimental development projects intended to deliver prototypes of systems. None of these projects is explicitly aimed at supporting the development of LAWS, as they are sometimes defined in CCW discussions (i.e. weapon systems that would be able to conduct an offensive mission in complete autonomy, without a human in or on the loop). However, a number of these projects could provide some of the building blocks for the development of such a system.

[5] Defense Advanced Research Projects Agency (DARPA), 'Collaborative Operations in Denied Environment (CODE)', <http://www.darpa.mil/program/collaborative-operations-in-denied-environment>.

[6] Hambling, D., 'US Navy plans to fly first drone swarm this summer', Defense Tech, 4 Jan. 2016, <http://www.defensetech.org/2016/01/04/u-s-navy-plans-to-fly-first-drone-swarm-this-summer/>; and Tadjeh, J., 'Navy long-endurance underwater drone to begin deep ocean navigation', *National Defense Magazine*, Jan. 2016.

5. The private sector

In which areas of industry do relevant R&D efforts take place? For the reasons presented in section 2, providing a comprehensive mapping of the private sector landscape with regard to innovations that could shape the future of autonomy in weapon systems is not feasible within the scope of this working paper. However, some general observations can be made about the industry sectors where significant R&D work is taking place.

I. Autonomy in industry

The robotics industry

The robotics industry is the sector where the most significant R&D efforts are carried out.[1] However, autonomy is not a priority for all stakeholders within that industry. The main dividing line is between 'industrial' robotics and 'interactive' or 'service' robotics (see box 4).[2] Industrial robotics, which actually represents the largest segment of the robotics industry, has historically had little to no interest in autonomy, as the robots developed in that segment are designed to perform repetitive, pre-programmed tasks in a very controlled environment.[3] Service/interactive robots, on the other hand, because they are intended to assist humans in various tasks and possibly evolve in dynamic conditions, usually need to include some level of autonomy in their functioning. Thus, R&D efforts that are of relevance to this discussion are primarily related to those types of robots.

Service/interactive robots come in all shapes and sizes—from small robotic insects to large UGSs—and have very different types of military and commercial applications.[4] Therefore, there are many possible ways to compartmentalize the robotics industry. The extent to which service/interactive robots need to, and can, work autonomously varies significantly, and depends on the intended end use and the nature of the working environment.

Autonomy is particularly attractive for tasks that are dangerous, dirty or dull for humans to perform or supervise. Such tasks could include logistics, driving, piloting and inspection and exploration in remote or dangerous environments. For many robotic systems, autonomy is also a safety requirement. UAVs flying in a cluttered airspace, for instance, need autonomous sense and avoidance capabilities.

At the same time, it has been established that the more complex a robot's actions need to be or the more the end use necessitates interactions with humans or unstructured environments, the harder it is to render the robot autonomous. Full robot autonomy is, therefore, generally much easier to engineer for civilian applications

[1] The 'robotics industry' can be defined as one that develops single electro-mechanical devices or platforms that can interact with, and execute tasks in, the real world. The exact borders of the industry are difficult to delineate.

[2] An 'industrial robot' is defined by the International Federation of Robotics (IFR) as 'an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications'. According to the IFR, a 'service/interactive robot' is 'a robot that performs useful tasks for humans or equipment excluding industrial automation application', International Federation of Robotics, <http://www.ifr.org/>.

[3] The emergence of so-called collaborative robots has begun to change the dynamic in the industrial robotics segment. Collaborative robots are industrial manipulators that are intended to work safely alongside humans. Tobe, F., 'Why co-bot will be a huge innovation and growth driver for robotics industry', IEEE Spectrum, 30 Dec. 2015, <http://spectrum.ieee.org/automaton/robotics/industrial-robots/collaborative-robots-innovation-growth-driver>.

[4] In this paper the 'robotics industry' is narrowly defined (see note 1). Arguably, the definition could be widened to also include the development and production of hardware and software components on which robotics platforms are created. It is useful, however, to distinguish between the narrow robotics industry and the robotics industrial base. The robotics industry focuses on companies that assemble and integrate robotic platforms, while the robotics industrial base encompasses a larger set of companies that provide the components used in robotic platforms.

Box 4. The robotics industry

Types of application

There are many possible ways to compartmentalize the robotics industry. It is most often divided in two, with on the one hand industrial robotics and on the other service/interactive robotics. The service/interactive robotics industry can be divided into three segments: *Household* for entertainment or leisure (e.g. hobbyist drones) or the execution of simple domestic tasks (e.g. vacuum cleaners, lawn mowers); *Commercial* for professional civilian use (e.g. mining and exploration, agriculture and logistics); and *Government* for military, law enforcement or civil security applications (e.g. intelligence surveillance and reconnaissance, search and rescue, weapon delivery, bomb ordnance disposal).[a]

According to World Robotics statistics, the majority of the robots on the market are destined for civilian use.[b] The market for military robots experienced significant growth in the 2000s thanks to US-led military interventions in Afghanistan and Iraq. The end of these interventions, however, has slowed the demand and created some uncertainty in the market, leading to a number of companies that were present in that segment diverting their military activity (e.g. iRobot) or increasing their focus on commercial applications (e.g. Lockheed Martin, Textron).

Types of operating environment

Robots can be subdivided into three categories: unmanned aerial systems (also known as unmanned aerial vehicles, UAVs), unmanned ground systems (UGSs) and unmanned maritime systems (UMSs). The UAV market is by far the most robust and mature sub-sector of the robotics industry, industrial robots excluded. Market research estimated its value at $10.1 billion in 2015.[c] The UGS market is a fast-growing industry. According to market research, the global UGV market will grow from $6.4 billion in 2015 to $18 billion by 2020.[d] In comparison to the UGV and UAV sectors, the UMS sector is a rather small industry sector.[e] The UMS sector consists of two sub-segments: unmanned surface vehicles (USVs) and unmanned underwater vehicles (UUVs). The USV market was estimated at $437.6 million in 2016, and is forecast to reach $861.4 million by 2021. The UUS market was valued at $2.3 billion in 2015 and is expected to grow to $4 billion by 2020, at a compound annual growth rate of 11.9 per cent.

Innovation leadership

Based on the number of patents filed, the World Intellectual Property Organization (WIPO) reported in 2015 that the five most innovative countries in robotics between 2005 and 2011 were (in rank order) Japan, China, South Korea, the USA and Germany.[f] Chinese and German innovations are primarily related to industrial robots. Japan leads global research on service robots. Japan has long been one of the main innovators in robotics. Reportedly, Japan's robotics industry is particularly innovative in terms of the physical design of robots, while the US industry is known for its innovations in robotic thought processes.[g]

[a] Aceves-Jiminez, C. et al., *Final Report, Robotics and Autonomous Systems Industry, Spring 2013, Industry Study* (Dwight D. Eisenhower School for National Security and Resource Strategy: Washington, DC, 2013), p. 2.

[b] International Federation of Robotics, World Robotics 2016, Service Robots (2016), <http://www.ifr.org/fileadmin/user_upload/downloads/World_Robotics/2016/Executive_Summary_Service_Robots_2016.pdf>.

[c] MarketsandMarkets (M & M), *Unmanned Aerial Vehicles: Global Forecast 2020*, Market Report (M & M: Oct. 2015).

[d] MarketsandMarkets (M & M), *Unmanned Ground Vehicles: Global Forecast 2020*, Market Report (M & M: Jan. 2016).

[e] MarketsandMarkets, 'Unmanned Surface Vehicle (SV) market worth 861.37 million USD by 2021', Press release, [n.d.].

[f] World Intellectual Property Organization (WIPO), *World Intellectual Property Report 2015: Breakthrough Innovation and Economic Growth* (WIPO: Geneva, 2015).

[g] Waters, R., 'Are Japanese robots losing their edge to Silicon Valley', *Financial Times*, 11 Jan. 2016.

than military applications, as in the civilian context the robot's working environment will be non-adversarial, (relatively) structured, confined (inside a house or factory) or known. In these conditions, the engineers who design the robots can use different approaches to minimize the limitations of, or reduce the technical requirements on, sensing and control algorithms. For instance, engineers can thoroughly pre-map (or structure) the environment in which the robot will operate so that the robot does not need to identify everything with its sensors and make too many decisions.[5] This developmental path to autonomy is not appropriate in the case of military robots, which are expected to cope with unstructured and dynamic terrains as well as with the deployment of deception, assault and counter-autonomy technologies by adversaries.[6] This is one of the reasons why civilian autonomous robots cannot be adopted by the military without notable modifications.

The aerospace industry

Historically, the aerospace industry has had a key role in the development of autonomous flight capabilities. Automated functions have been found in pilots' cockpits for decades to assist or replace human action during phases of a flight.[7] In the civilian sector, innovation in this area has been driven by safety and economic concerns. Airline companies are primarily interested in the development of automated features that will make aircraft easier and safer to operate, and that will cut maintenance costs (e.g. by reducing the potential for minor damage caused on landing). Currently, a commercial airliner's cockpit is perhaps among the most advanced and complex human–machine teaming systems in operation. Civilian aircraft manufacturers (e.g. Airbus and Boeing) have had limited interest in the development of fully autonomous flight control systems—for the time being, commercial airlines want to keep a human in control. However, their financial investment and research efforts in the underlying technologies and procedures for safety control and the interaction of human-automated systems have contributed to the development of autonomous functions in UAVs. If a large UAV can take off and land autonomously, it is partly thanks to research efforts that civilian aircraft manufacturers have put into the development of automated functions in commercial aircraft. Commercial and military aircraft manufacturers are, in fact, the main suppliers of large and mid-size UAVs that are currently being used by military and commercial companies. Key manufacturers include Boeing, Elbit Systems, General Atomics, IAI and Northrop Grumman. These companies usually develop their own flight control systems, including the software elements that enable the platforms to operate autonomously for some part of the flight. The platforms that these companies produce typically require the active control of a human operator for the main part of a mission. It is technically possible to make them fly entire missions autonomously; however, there remains some cultural resistance within the military to a paradigm where humans would be in a supervisory role rather than an operating role.[8]

The automotive industry

Similar to the aerospace industry, autonomy has been a central element of the progress of the automobile manufacturing industry over the past two decades. Most cars, trucks and buses in current operation include a number of automated functions aimed at increasing safety and enhancing the driving experience. Standard features include

[5] A good illustration of this is the Google car. It is often presented as the apotheosis of autonomous systems development, while in reality the system cannot even recognize a traffic light signal by itself. US Department of Defense (DOD), Office of Technical Intelligence, Office of the Assistant Secretary of Defense for Research and Engineering, *Technical Assessment: Autonomy* (DOD: Washington, DC, Feb. 2015), p. 12.

[6] US Department of Defense (DOD), Defense Science Board, *Report of the Defense Science Board Summer Study on Autonomy* (DOD: Washington, DC, 2016), p. 13.

[7] For a history of automation in the aerospace sector see Lindell, D., *Our Robots, Ourselves* (Viking: New York, NY, 2015), pp. 69–111.

[8] Scharre, P., *Robotics on the Battlefield Part II: The Coming Swarm* (Centre for a New American Security: Washington, DC, Oct. 2014).

air bags, anti-lock braking systems, emergency seat belt retractors and power steering. Some higher-end cars include more sophisticated features such as automatic lane keeping, automatic parking, collision avoidance and cruise control.

The next frontier, however, is the development of self-driving vehicles. Over 30 companies are actively working on the development of self-driving vehicles, these include not only major carmakers (BMW, Ford, General Motors, Tesla, Toyota etc) but also major technology companies (Baidu, Google etc) and automobile service providers (e.g. Uber and Lyft).[9] Self-driving cars remain an emerging technology and the companies that develop them still disagree about when they might be commercialized on a large scale. Tesla estimates that this will happen in 2018, while Ford and Toyota suggest 2020.[10] In any event, efforts that are being put into the development of self-driving cars are significant for at least three main reasons. First, they generate important funding streams and a clear research agenda for the community of AI and robotics researchers. One notable illustration of this is the recent creation by Toyota of research centres located in two of the most prestigious US universities in the fields of AI and robotics: Stanford University and MIT.[11] The company committed $50 million in funding to these universities.[12]

Second, many of the engineering, ethical and legal problems that these companies are seeking to solve, in order to commercialize self-driving cars on a large scale, are common to many other types of civilian, but also military, autonomous systems (see box 5). These include:

1. Increasing the intelligence of computer vision systems to enable the safe use of autonomy in complex and populated environments;
2. Finding methods to ensure a trustworthy and reliable interaction and collaboration between humans and autonomous systems;
3. Finding methods to test, evaluate, verify and validate the capability, reliability, suitability and safety of autonomous systems intended to operate in complex and populated environments;
4. Determining how to program ethical rules into the command and control of autonomous systems;
5. Clarifying issues related to liability in the case of accident presented by autonomous cars (the self-driving car is a test-bed technology for the wider adoption and acceptance of autonomous systems); and
6. Finding methods to ensure the integrity of autonomous systems against the threats of spoofing and cyberattacks.

[9] 'Apple, Audi, Baidu/BMW, Bosch, DAF/Daimler/Iveco/MAN/Scania/Volvo, Delphi, Ford, General Motors, Google, Honda, Hyundai, Jaguar/Landrover, Mercedes, Microsoft, Mobileye, Nissan/Renault, Nvidia, PSA Groupe, Tata Elixsi, Tesla, Toyota, Uber, Volkswagen, Volvo, Yutong: 30 corporations working on autonomous vehicles', CB Insights, accessed 18 Apr. 2016, <https://www.cbinsights.com/blog/autonomous-driverless-vehicles-corporations-list/>.

[10] 'When will self-driving cars be available to consumers?', Quora, accessed Feb. 2016, <https://www.quora.com/When-will-self-driving-cars-be-available-to-consumers?redirected_qid=6670450>; Caddy, B., 'Toyota to launch first driverless car in 2020', *Wired*, 8 Oct. 2015; and Lambert, F., 'BMW will launch the electric and autonomous INext in 2021, new i8 in 2018 and not much in-between', Electrek, 12 May 2016, <http://electrek.co/2016/05/12/bmw-electric-autonomous-inext-2021/>.

[11] Toyota Global Newsroom, 'Toyota will establish new artificial intelligence research and development company', 6 Nov. 2015.

[12] With reference to the level of investment in AI by carmakers, some carmakers (such as Toyota) have established themselves in the top 20 of the world's leading software developers. Markoff, J., 'Toyota invest $1 billion in artificial intelligence in U.S.', *New York Times*, 6 Nov. 2016.

Third, the volume of production of the commercial car industry usually generates major economies of scale in the production of hardware and software components. Hence, the growth of the driverless car market holds the promise of bringing down the cost of sensors and computer chip technologies for large robotics platforms, including military platforms.[13]

The ICT industry

The ICT industry plays a central role in the development of autonomy as it drives innovation and cost reduction of the computer hardware and software components that create autonomy. Two relatively recent developments are worth noting here. First, the boom of the smart phone industry has had a major impact on the availability, cost, performance and size of batteries, computer chips and sensor technologies—including vision-based sensors (video cameras), tactile sensors (touch screens), GPS sensors, and motion sensors such as the inertial measurement unit (IMU). Second, the introduction of the Kinect in 2011—a sensor system developed by Microsoft for its video game platform X Box—has played a key role in driving progress as it provided the robotics community with a very low-cost and efficient three-dimensional (3-D) scanner system.[14] Prior to the Kinect, such scanner systems were either very expensive or unreliable.[15] The decreasing cost and increasing availability of sensor technologies have made robotics platforms much more affordable to develop and acquire. That trend has notably fuelled the emergence in recent years of low-cost robotics platforms such as hobbyist drones.

Major Internet services companies like Alphabet (Google, USA), Amazon (USA), Baidu (China) and Facebook (USA), which have experienced exponential growth over the past decade to the point of becoming the most influential companies in the ICT sector, are also playing an increasingly active and determining role in shaping the future of AI and robotics.[16] Reportedly, these companies are currently luring the most talented individuals in AI and robotics research away from universities.[17] The large financial resources at the disposal of these companies have also allowed them to acquire, in recent years, some of the companies that are deemed to be at the forefront of innovation in AI and robotics.[18] The most notable deals to have taken place so far include the acquisitions by Google of Boston Dynamics in 2013 (which has since been divested) and of DeepMind in 2014.[19] DeepMind is behind the design of the AlphaGo

[13] US Department of Defense (DOD), Office of Technical Intelligence, Office of the Assistant Secretary of Defense for Research and Engineering (note 5), p. 11.

[14] 3-D scanner systems are 3-D perception sensors that enable robots to map out their environment, and detect and manipulate obstacles as well as recognize motions, objects and faces.

[15] The future development of driverless vehicles, which will rely on 3-D perception systems for autonomous navigation, is expected to further improve the efficiency, and more importantly, the availability of 3-D perception sensors.

[16] The interest of these companies in these areas is commonly driven by a desire either to diversify their portfolios into new markets (e.g. Alphabet's and Baidu's move into the autonomous car business) or to improve the delivery of existing products and services (e.g. Amazon wanting to use UAVs to deliver packages). González, Á., 'Hands, heads and robots work in sync at Amazon warehouses', *Seattle Times*, 9 Apr. 2016; Tam, P.-W., 'Facebook's developer conference kicks off', *New York Times,* 12 Apr. 2016; and Simonite, T., 'Teaching machines to understand us', *MIT Technology Review*, 6 Aug. 2015.

[17] Levy, S., 'How Google is remaking itself as "Machine Learning First Company"', *Backchannel*, 22 June 2016; and Hernandez, D. and King, R., 'Universities' AI talent poach by tech giants', *Wall Street Journal*, 24 Nov. 2016.

[18] Apple and Google have nearly $180 billion and $60 billion in cash respectively, dwarfing the amount held by any company within the defence sector. In fact, Google has sufficient cash to buy out any of the major defence contractors, which illustrates the size and power of both the company and the growing global technology sector. Lynn III, W. J., 'The end of the military–industrial complex', *Foreign Affairs*, Nov./Dec. 2014.

[19] Gibbs, S., 'What is Boston Dynamics and why does Google want robots', *The Guardian*, 17 Dec. 2013; and Smith, R., 'Google is selling Boston Dynamics: but who's buying?', Motley Fool, 25 Apr. 2016, <http://www.fool.com/investing/general/2016/03/26/googles-selling-boston-dynamics-but-whos-buying.aspx>.

Box 5. Challenges related to commercialization of self-driving vehicles

Engineering
Driving is not just about navigation and obstacle avoidance, it is also about social interaction: driving in an urban environment requires frequent interaction with humans—other drivers, cyclists and pedestrians. Machines remain poor at understanding and predicting the behaviour of human road users. The state of the art in computer vision permits self-driving cars to recognize only basic behaviours (walking, running and looking away). The limitation in perception and communication represents an obstacle to the use of self-driving cars in densely populated environments like city centres. As vehicle situational awareness improves, carmakers are working on challenging engineering problems similar to those faced by the military in terms of autonomous capability for targeting and surveillance (i.e. recognizing human behaviour).

Human control
Carmakers also have radically different approaches as to how self-driving vehicles should be developed, and how much autonomy they should have. Companies with a background in the information communication technology (ICT) sector, such as Google or Uber, are aiming to develop fully autonomous vehicles, which might not even include a steering wheel. Traditional carmakers, on the other hand, have a more conservative approach, and favour a 'shared control' model where autonomy would allow vehicles to work in collaboration with human drivers, rather than replacing them.[a] It is unclear for now which model will prevail, as experts have radically different views about which model will guarantee maximum safety.

Ethical
The most salient problem is the so-called car crash dilemma: how should the vehicle deal with a situation where it has to choose between making a manoeuvre that will keep its passenger safe but put a pedestrian or another car driver at risk, and making another manoeuvre that will keep the pedestrian or the other car driver safe but put its passenger at risk? How carmakers, transport regulators and insurance companies resolve this dilemma will be instrumental in determining how societies approach the ethical governance of autonomous systems in the future.

Legal
The development of the self-driving car industry will also contribute to the resolution of some of the legal questions that autonomy poses, notably in terms of liability. Self-driving will only be widely used once insurance companies, transport regulators and carmakers have agreed on who is to blame when a self-driving car is involved in an accident. In that regard, the legal concerns associated with the use of self-driving cars might also push the car industry to develop common standards for testing and evaluation procedures. As it stands, the autonomous systems community still lacks a proper methodology to test complex autonomous control systems. Considering the vested interest that the carmakers have in demonstrating the safety and reliability of their vehicles, it is likely that they will play a crucial role in the development of standards for the validation and verification of autonomous systems.

[a] Toyota's main research project on autonomous vehicles is called 'human-centered artificial intelligence for future intelligent vehicles and beyond'. Some carmakers, including Toyota, have even created research centres directly within universities. Toyota's centres are based at MIT and the University of Stanford, both of which are in the USA. Toyota Global Newsroom, 'Toyota will establish new artificial intelligence research and development company', 6 Nov. 2015.

program (developed to play the board game Go) and is considered to be conducting some of the most cutting-edge research on machine learning and AGI.[20]

The major Internet services companies are also able to pour vast cash resources into R&D, including basic research. Google has perhaps made the most visible of these

[20] 'Google to buy artificial intelligence company DeepMind', Reuters, 26 Jan. 2014; and 'The last AI breakthrough DeepMind made before Google bought for $400m', Physics arXiv Blog, 29 Jan. 2014, <https://medium.com/the-physics-arxiv-blog/the-last-ai-breakthrough-deepmind-made-before-google-bought-it-for-400m-7952031ee5e1#.v7a785ixa>.

research efforts to date.[21] In 2011 it started the Google Brain project, which has a team of researchers dedicated to machine learning with a focus on deep learning.[22]

It is also worth noting that many of the larger Internet services companies are working on a number of commercial applications of autonomy that have considerable military potential. These applications range from autonomous delivery platforms and driverless vehicles to speech interfaces. The AI applications that Google, Baidu and Facebook are developing for analysis and referencing of web content, notably pictures and videos, are not significantly different from the image-interpretation systems that military planners are willing to acquire to help military personnel to process raw video footage captured by surveillance UAVs.[23]

The surveillance industry

Companies in the surveillance industry, notably the electronic surveillance segment, are developing a number of niche capabilities that could be instrumental to the further development of automated target recognition technologies and information processing on-board unmanned surveillance systems. Biometric companies, such as Sagem, are developing biometric recognition systems that can identify people in a non-collaborative context.[24] These systems are intended for security professionals (i.e. law enforcement, intelligence agencies and private security companies that work in the areas of criminal investigation, border control and counterterrorism) who need to be able to identify the identity of individuals 'on the fly' using photographs or video footage captured by surveillance cameras. These systems could potentially be used by the military during intelligence, surveillance and reconnaissance missions to support the identification of high-value military targets. Another relevant niche capability is video-surveillance analysis.

The arms industry

As discussed in section 2, the arms industry is dependent on demand from the military.[25] The R&D of arms-producing companies is mainly derived from government-funded projects or well-defined acquisition programmes. It has not been possible to assess what their internal R&D departments focus on.

Historically, arms industry innovations in autonomous technologies have been driven by demand for two types of systems. The first type is the automatic defensive system. Examples include (*a*) the Goalkeeper close-in weapon system produced by Thales for the Netherlands; (*b*) the Quick Kill active vehicle protection system produced by Raytheon for the USA; and (*c*) the Super aEgis anti-personnel sentry weapon system produced by DoDAMM for South Korea. The second type of system includes smart missiles and munitions such as (*a*) the long range anti-ship smart missile (LRASM) produced by Lockheed Martin for the USA; and (*b*) the Harpy loitering munitions produced by Israel Aerospace Industries for Israel. Both types of systems

[21] Levy (note 17).

[22] Levy (note 17); and O'Brian, C., 'Google creates new European research group to focus on machine learning', Venture Beat, 16 June 2016, <http://venturebeat.com/2016/06/16/google-creates-new-european-research-group-to-focus-on-machine-learning/>.

[23] As it stands, all the data that is captured by the cameras of unmanned systems has to be monitored and analysed by humans. The development of on-board computer vision algorithms that could identify situations of interest and cue them to human analysts would allow the military to significantly reduce its manpower burden and the need for robust bandwidth. Tucker, P., 'Robots won't be taking these military jobs anytime soon', Defense One, 22 June 2015, <http://www. defenseone.com/technology/2015/06/robots-wont-be-taking-these-military-jobs-anytime-soon/116017/>.

[24] That is a situation where the individual is not actively following an identification procedure in a structured context (e.g. through a border control or an identification check).

[25] Aceves-Jiminez, C. et al., *Final Report, Robotics and Autonomous Systems Industry, Spring 2013, Industry Study* (Dwight D. Eisenhower School for National Security and Resource Strategy: Washington, DC, 2013).

have in common their reliance on in-built sensors and target recognition software—a technology that has existed for over a decade—that allow them to identify targets autonomously based on defined signatures. Smart missiles and munitions also generally include some autonomous flight capabilities. The two types of systems are mainly developed and produced by large defence corporations based in major arms-producing regions/countries: Western Europe (Germany, France, Italy, the Netherlands, Poland, Sweden and the UK) and China, Russia, Israel, South Korea and the USA (see Appendix C).

The arms industry's most visible current R&D efforts on autonomy are chiefly related to the increasing use of unmanned systems (specifically self-driving vehicles and UAVs), which has grown considerably over the past decade. Self-driving vehicles present new opportunities for the military.[26] Their use would enable military forces to automate some parts of the logistical chain and thereby increase manpower efficiency and reduce the risks to military personnel. Considering that the design of commercial self-driving vehicles has limited value in a military context, arms-producing companies have a key role to play in the development of military-capable, self-driving vehicles. Companies that have made the most significant advances in the development of autonomous vehicles for the military include: Boeing (USA), ECA Robotics (France), General Dynamics (USA), G-Nius (Israel), Lockheed Martin (USA), Nexter (France), Oshkosh (USA), Qinetic (UK) and Thales (France).[27]

Most military UAVs have limited capabilities in contested airspace. The USA and a group of countries in Western Europe are therefore looking to develop stealth UAVs that would be able to operate autonomously in communication-denied airspace to conduct surveillance missions or targeted strikes. In the USA, development is being led by Lockheed Martin, while in Western Europe development is being led by BAE Systems (Taranis Programme), and Dassault and Saab (Neuron Programme).[28]

II. Conclusion

Civilian industry—led by major ICT companies and automobile manufacturers—is the driving force behind innovation in autonomous systems. A number of civilian autonomous technologies have a military value, either because they could be adopted off-the-shelf by the military, or because the R&D efforts that support their development could serve to improve autonomous capabilities in the military sphere. The role of defence companies remains crucial, since commercial autonomous technologies can rarely be adopted by the military without substantial modifications.

[26] US Department of Defense (DOD), Office of Technical Intelligence, Office of the Assistant Secretary of Defense for Research and Engineering (note 5), p. 11.

[27] The company G-Nius discontinued operations in Apr. 2016 due to commercial difficulties. Opall-Rome, B., 'G-Nius folds from low interest in unmanned ground systems', *Defense News*, 11 Apr. 2016.

[28] Sayer, K., *A World of Proliferated Drones: A Technology Primer* (Center for New American Security: Washington, DC, 2015).

6. Conclusions: key findings and takeaways for the Convention on Certain Conventional Weapons discussions

This working paper is intended to help CCW delegates and the interest public to understand where innovations that are relevant to the advance of autonomy in weapon systems are taking place. It maps out R&D efforts conducted by academia, governmental research agencies and the private sector. Its key findings are presented here from three different perspectives: (*a*) a science and technology perspective (the field of R&D), (*b*) a geographical perspective (the location of key R&D institutions), and (*c*) a sector perspective (whether innovation is driven by civil or military research).

I. Key findings

Key finding 1. Where are relevant innovations taking place? A science and technology perspective

At a basic science and technology level, advances in autonomy are mainly taking place in the fields of AI and robotics. These fields partially overlap. In addition to sharing a number of research issues, they have in common the fact that they are interdisciplinary and have contact points with many other fields of science and technology, including biology, psychology, linguistics and mathematics.

Key finding 2. Where are relevant innovations taking place? A geographical perspective

Several elements seem to indicate that the USA is the country that currently leads innovation in the areas of science and technology that are the most important to the future of autonomy in weapon systems. US universities are leading the production of scientific publications with AI and robotics research. US military research agencies have financial resources that agencies in other countries (reportedly) cannot match. US agencies are also currently engaged in numerous R&D projects that could directly and indirectly generate important advances in autonomy in weapon systems. Companies that are currently making the most significant R&D efforts in AI and robotics are primarily US-based. Outside the USA, academic institutions, government research agencies and private companies that are deemed to be engaged in the most significant R&D work are predominantly based in Western Europe and East Asia.

Key finding 3. Where are relevant innovations taking place? A sector perspective

It is established that the civilian sector leads innovation in autonomous technologies. On the industry side, the most influential players are major Internet-based services platforms like Alphabet (Google, USA), Amazon (USA) and Baidu (China), and carmakers like Toyota that have moved into the self-driving car business. Their role is significant in the sense that they are developing a number of AI applications and autonomous robots with military potential (including autonomous delivery UAVs, computer vision systems for video analysis, self-driving vehicles and speech recognition interfaces) and also because they dedicate substantial resources to basic R&D relating to autonomy. Traditional arms producers have been involved in the development of autonomous technologies but the amount of resources that these companies allocate to R&D is far less than that mobilized by large commercial corporations in the civilian sector. However, the role of defence companies remains crucial, since commercial autonomous technologies can rarely be adopted by the military without substantial modifications. Indeed, commercial companies have been able to develop robotic systems that are highly autonomous in their functioning, primarily because autonomy is more easily created for civilian uses. The fact that the military sector trails behind the civilian sector, is partly because developing advanced autonomous capabilities for battlefield conditions remains, in many regards, a very difficult engineering challenge.

II. Key takeaways for the CCW discussions

The key takeaways for the future CCW discussions can be summarized in three points.

Takeaway 1. Efforts to monitor and control innovation should focus on the development end of the R&D cycle

Fundamental innovations in the fields of AI and robotics are typically dual use. The divergence between civilian and military innovation generally emerges towards the development end of the R&D cycle, since civilian and military products often need to meet different performance criteria. Should CCW delegates eventually engage in a formal discussion aimed at monitoring or regulating R&D efforts that could lead to the development and production of LAWS, they should focus on the development end of the R&D cycle, as this is where the actual capabilities of LAWS will be concretely created. Attempting to monitor and control R&D at the more basic research side would be challenging from a practical perspective and possibly problematic as it could threaten civilian innovation.

Takeaway 2. The risk of weaponization of civilian technologies by non-state actors deserves more scrutiny

The civilian sector is leading the development of autonomous technologies. It is now possible to acquire off-the-shelf robotics systems that feature advanced autonomous capabilities. These may be adopted, modified and weaponized by states but also, and more worryingly, by non-state actors seeking, for instance, to conduct terrorist operations. This scenario has not yet received great attention within the CCW discussions on LAWS despite the fact it represents an imminent humanitarian risk. One possible option to structure constructive discussions on that topic could be to engage in dialogue with the civilian industry on measures that could possibly limit the availability of civilian autonomous technologies to terrorist organizations.

Takeaway 3. Facilitate the exchange of experience with the civilian sector

Future discussions on the development and control of autonomy in weapon systems could usefully benefit from further exchanges of experience with the civilian sector considering that a number of issues that are central to discussion on LAWS—including how to define autonomy and how to operationalize meaningful human control or test the predictability of autonomous technologies—have already been or are currently being actively discussed within the civilian sphere.

Appendix A: Key research institutions in the fields of artificial intelligence and robotics

Table 2. Top 10 research institutions in the field of artificial intelligence based on volume of academic publications in sample of relevant topics, 2011–16

Ranking by publication topic

Rank	Artificial intelligence	Machine learning	Human –machine interaction	Natural language processing	Computer vision
1	Massachusetts Institute of Technology (USA)	Microsoft (USA)	Microsoft (USA)	Microsoft (USA)	Microsoft (USA)
2	Carnegie Mellon University (USA)	Max Planck Society (Germany)	Carnegie Mellon University (USA)	Google (USA)	Massachusetts Institute of Technology (USA)
3	Microsoft (USA)	Carnegie Mellon University (USA)	Massachusetts Institute of Technology (USA)	Max Planck Society (Germany)	Stanford University (USA)
4	Stanford University (USA)	IBM (USA)	University of Washington (USA)	Stanford University (USA)	Chinese Academy of Science (China)
5	University of Toronto (Canada)	Google (USA)	Georgia Institute of Technology (USA)	Carnegie Mellon University (USA)	ETH Zurich (Switzerland)
6	University of California, Berkeley (USA)	Stanford University (USA)	University College London (UK)	IBM (USA)	University of California (USA)
7	IBM (USA)	Chinese Academy of Science (China)	Stanford University (USA)	Massachusetts Institute of Technology (USA)	Carnegie Mellon University (USA)
8	Centre national de la recherche scientifique (France)	University of Toronto (Canada)	University of California, Berkeley (USA)	Centre national de la recherche scientifique (France)	Tsinghua University (China)
9	Nayang Technology University (South Korea)	Massachusetts Institute of Technology (USA)	IBM (USA)	University of Illinois, Urbana-Champaign (USA)	French Institute for Research in Computer Science and Automation (France)
10	University College London (UK)	University of California, Berkeley (USA)	Newcastle University (UK)	University of Edinburgh (UK)	University of California, Berkeley (USA)

Source: Microsoft Academic Search Index, accessed 9 Dec. 2016, <http://academic.research.microsoft.com/>.

Table 3. Top 20 research institutions in the field of robotics based on volume of academic publications in sample of relevant topics, 2000–16

Ranking by publication topic

Rank	Autonomous systems	Robotics	Mobile robots
1	Carnegie Mellon University (USA)	Massachusetts Institute of Technology (USA)	Carnegie Mellon University (USA)
2	Massachusetts Institute of Technology (USA)	Carnegie Mellon University (USA)	Massachusetts Institute of Technology (USA)
3	University of Washington (USA)	Robotics Institute (USA)	Robotics Institute (USA)
4	Robotics Institute (USA)	Stanford University (USA)	University of Southern California (USA)
5	Imperial College London (UK)	John Hopkins University (USA)	Georgia Institute of Technology (USA)
6	University of Toronto (Canada)	University of Southern California (USA)	University of Freiburg (Germany)
7	Georgia Institute of Technology (USA)	Centre national de la recherche scientifique (France)	University of Pennsylvania (USA)
8	Univeristy of Michigan (USA)	University of Pennsylvania (USA)	Stanford University (USA)
9	University of California (USA)	Harvard University (USA)	Centre national de la recherche scientifique (France)
10	Stanford University (USA)	French Institute for Research in Computer Science and Automation (France)	ETH Zurich (Switzerland)
11	Centre national de la recherche scientifique (France)	Vattikuti Urology Institute (Finland)	École Polytechnique Fédérale de Lausanne (France)
12	University of Illinois, Urbana-Champaign (USA)	Columbia University (USA)	University of Tokyo (Japan)
13	Ohio State University (USA)	Cleveland Clinic (USA)	Tokyo Institute of Technology (Japan)
14	Beckman Institute for Advanced Science and Technology (USA)	Jet Propulsion Laboratory (USA)	University of Sydney (Australia)
15	National Technical University Athens (Greece)	École Polytechnique Fédérale de Lausanne (France)	University of Michigan (USA)
16	University of California, Berkeley (USA)	University of Illinois, Urbana-Champaign (USA)	Jet Propulsion Laboratory (USA)
17	Technische Universität München (Germany)	University of Tokyo (Japan)	University of Washington (USA)
18	Arbor Networks (USA)	Georgia Institute of Technology (USA)	French Institute for Research in Computer Science and Automation (France)
19	Deutsche Telekom (Germany)	Imperial College London (UK)	University of California (USA)
20	University of California, Santa Barbara (USA)	Yonsei University (South Korea)	University of California, Berkeley (USA)

Source: Microsoft Academic Search Index, <http://academic.research.microsoft.com/>.

Appendix B: Government conducted or funded research and development projects related to autonomy

I. United States

Table 4.1. Defense Advanced Research Projects Agency (DARPA)

Name	Area of application/objective
General AI	
Explainable Artificial Intelligence	Machine learning: create machine learning models that will have the ability to explain their rationale, characterize their strengths and weaknesses, and convey an understanding of how they will behave in the future to humans.
Probabilistic Programming for Advanced Machine Learning (PPAML)	Machine learning: construct new, easier machine learning languages for increased reach, effectiveness, and a larger amount of applications.
Battlefield intelligence	
Insight	Intelligence analysis: develop more effective and efficient means to receive, correlate, analyse, report and share intelligence. The system would receive, index and store incoming data from multiple sources. It would then analyse and correlate that information, and request and share other relevant information with analysts and data providers. Insight's automated backend processing capabilities would include behavioural learning and prediction algorithms to help analysts discover and identify potential threats and explore hypotheses about those threats' potential activities.
Media Forensics (MediFor)	Computer vision: develop systems that can automatically detect image manipulation of images and videos.
Memex	Search engine: next-generation search technologies for the deep web, which is currently hidden for normal search engines.
Military Imaging and Surveillance technology (MIST)	Computer vision for targeting: provide high resolution 3-D images to locate and identify targets at long ranges, distances sufficient to allow stand-off engagement.
Target Recognition and Adaptation in Contested Environments (TRACE)	Automated target recognition: accurate, real-time, low-power target recognition system for tactical airborne surveillance and strike applications.
Visual Media Reasoning (VMR)	Computer vision of intelligence analysis: develop a method that allows users to ask queries of photo content. The systems could extract relevant information for human analysts and alert them to scenes that warrant an analyst's expert attention.
Human–machine communication	
Aircrew Labor In-Cockpit Automation System (ALIAS)	Supervise autonomy via voice command and control: develop a highly adaptable automated system that can move from aircraft to aircraft and execute missions from take-off to landing from a simple touch and voice recognition interface.
Big Mechanism	Natural language processing for information processing: extract relevant information from large amounts of scientific articles to make causal models (starting with cancer research).
Broad Operational Language Translation (BOLT)	Natural language processing for translation: create new techniques for automated translation and linguistic analysis that can be applied to the informal genres of text and speech common in online and in-person communication. It is aimed at enabling communication with non-English-speaking populations and identifying important information in foreign-language sources.
Deep Exploration and Filtering of Text (DEFT)	Natural language processing: develop techniques for understanding implicit meaning in text—things that a human understands but a computer does not.

Name	Area of application/objective
Low Resource Languages for Emergent Incidents (LORELEI)	Natural language processing for translation: basic understanding of languages for which there are low resources in short time frames (24 hours), aimed at emergency incidents.
Communicating with Computers (CwC)	Natural language processing for symmetric human–machine communication: enable symmetric communication between people and computers in which machines are not merely receivers of instructions but collaborators, able to harness a full range of natural modes, including language, gesture and facial or other expressions.
Command and control and collaborative autonomy	
Collaborative Operations in Denied Environment (CODE)	Collaborative autonomy for targeting: develop fundamental underlying technology for networks of heterogeneous unmanned systems, under the control of a single human supervisor, to collaborate, find, track, identify and engage targets.
Squad x Core Technologies	Multi-vehicle command and control: enable control of multiple heterogeneous systems, manned and unmanned for increased situational awareness and kinetic engagement during patrols.
Distributed Battle Management (DBM)	AI for battle management: develop decision aids to assist airborne battle managers and pilots in air-to-air and air-to-ground combat, managing both manned and unmanned systems.
Mathematics of Sensing, Exploitation and Execution (MSEE)	Sensor fusion: common language for all sensors to understand and learn in an unsupervised setting.
Resilient Synchronized Planning and Assessment for the Contested Environment (RSPACE)	AI for battle management: develop a system for battle management in a contested environment in the aerospace domain with network constraints.
Autonomy in unmanned systems	
Anti-Submarine Warfare Continuous Trail Unmanned Vessel (ACTUV)	Unmanned maritime systems: develop long-term autonomous unmanned vessel for anti-submarine warfare.
Distributed Agile Submarine Hunting (DASH)	Unmanned maritime systems: develop drop-and-forget sonar devices and unmanned underwater vehicles to find and hunt submarines.
Fast Lightweight Autonomy (FLA)	Unmanned aerial systems: develop small and fast autonomous unmanned aerial vehicles.
Heterogeneous Aerial Reconnaissance Team (HART)	Unmanned aerial systems: develop unmanned aerial vehicles that could provide continuous, real-time, 3-D surveillance of large urbanized areas. The systems should be capable of autonomous flight, mission execution and identification of suspicious activity.
Hydra	Unmanned maritime systems: develop network of underwater pods that can deploy unmanned underwater vehicles and unmanned aerial vehicles for intelligence surveillance and reconnaissance and countermine measures.
Inbound, Controlled, Air-Releasable, Unrecoverable Systems (ICARUS)	Unmanned aerial systems: develop unmanned aerial vehicles that can drop supplies (e.g. for Special Ops on missions) that vanish after a certain number of hours or in sunlight.
Legged Squad Support System (LS3)	Unmanned ground systems: develop legged robots capable of locomotion in complex terrains.
Long Range Anti-Ship Missile (LRASM)	Missile technology: develop anti-ship missile which would be capable of autonomous targeting relying on on-board targeting systems to independently acquire the target without the presence of prior, precision intelligence, or supporting services such as Global Positioning System navigation and data-links.
Maximum Mobility Manipulation (M3) programme	Robot manipulation: create a significantly improved scientific framework for the rapid design and fabrication of robot systems, and greatly enhance robot mobility and manipulation in natural environments.

Name	Area of application/objective
Transformer X	Unmanned aerial systems/unmanned ground systems: develop a terrain-independent transportation system for logistics, personnel transport and tactical support missions for small ground units.

Source: Defense Advanced Research Projects Agency, <http://www.darpa.mil>.

Table 4.2. Air Force Office of Scientific Research

Name	Area of application/objective
General AI	
Computational Cognition and Machine Intelligence	AI: conduct basic research into fundamental principles needed for autonomous and mixed human–machine systems. Sub-areas: Computational Cognition, Robust Decision Making and Machine Intelligence.
Battlefield intelligence	
Optoelectronics and Photonics	Computer vision: increase capabilities in image and data capture, processing, storage, and transmission for applications in surveillance, communications, computation, target discrimination, and autonomous navigation.
Human–machine communication	
Science of Information, Computation, Learning and Fusion	Natural language processing for information processing: fundamental research to extract relevant information from complex, disparate information sources.
Trust in Autonomy for Human Machine Teaming	Human–machine interaction: understand the trust dynamic between humans—pilots, intelligence, surveillance and reconnaissance operators, analysts—and robots, and develop advanced human–robot teaming concepts.
Command and control and collaborative autonomy	
Dynamics and Control	Control systems for unmanned aerial systems: develop adaptive control and decision-making algorithms for deployment of autonomous aerospace vehicles in uncertain environments.

Source: Air Force Office of Scientific Research (AFOSR), Information and Networks, <http://www.wpafb.af.mil/Welcome/Fact-Sheets/Display/Article/842033>.

Table 4.3. Army Research Laboratory

Name	Area of application/objective
Battlefield intelligence	
Unattended Ground Sensor (UGS) Technology	Perception technology for intelligence, surveillance and reconnaissance: develop technology concepts, sensors, algorithms, sensor employment planning tools, and hardware modules that support autonomous classification and discrimination between people, animals, vehicles, aircraft, and ammunition fire.
Autonomous Dynamic Analysis of Metaphor and Analogy (ADAMA)	Natural language processing: develop a software system that can automatically analyse metaphorical speech in 5 different languages.
Autonomy in unmanned systems	
Autonomous Mobility Applique System (AMAS)	Navigational autonomy in unmanned ground systems: develop an add-on kit for military logistics vehicles to enable autonomous driving in convoys.
Micro Autonomous Systems and Technology (MAST)	Swarming: fundamental research into the development of swarms of micro-robots (15 mm) in sensing, navigation, communication, and cooperation.
Common Light Autonomous Robotics Kit (CLARK)	Unmanned ground systems: develop small, remotely controlled or semi-autonomous robots that provide the ability to conduct close reconnaissance and to investigate potential threats from safe distances, building on MAST.
Squad Multi-Purpose Equipment Transport (SMET)	Autonomy for logistics: develop a semi-autonomous vehicle for transport of goods.

Source: Hatfield, S., 'Army robotics modernization', 25 Aug. 2015, <http://www.ndia.org/Divisions/Divisions/Robotics/Documents/Hatfield.pdf>; and Army Research Laboratory, <https://www.arl.army.mil/www/default.cfm>.

Table 4.4. Marine Corps War Fighting Laboratory

Name	Area of application/objective
Human–machine communication	
Unmanned Tactical Autonomous Control and Collaboration (UTACC)	Reduce cognitive load on marines, through a team of autonomous air and ground robots for multi-dimensional intelligence, surveillance and reconnaissance; development of Distributed Real-time Autonomously Guided Operations Engine (DRAGON).
Intuitive Robotic Operator Control	Robots recognizing and obeying hand/arm signals under limited radio frequency (RF) options.
Combat Robotics System (CRS)	Fundamental research programme to explore dynamics of man–machine interaction.
Semantic and Visual Representation of Autonomous System Perceptual Data for Effective Human/Machine Collaboration	Improve understanding of how to achieve cognitively compatible and shared semantic and visual representations of data, knowledge, and information collected by the autonomous system for both the human and the computer (part of the Science of Autonomy programme).
Autonomy in unmanned systems	
Autonomous Mobility Applique System (AMAS)	Add-on kit for military logistics vehicles to enable autonomous driving in convoys.
Ground Unmanned Support Surrogate (GUSS)	Optionally unmanned and autonomous vehicles for dismounted warfighters.

Note: Access to the US Army website is restricted outside the USA. Details about projects listed here were found using secondary sources.

Source: Marine Corps War Fighting Laboratory, <www.mcwl.marines.mil/>.

Table 4.5. Office of Naval Research

Name	Area of application/objective
General AI	
Adaptive testing of autonomous systems	Validation and verification: develop technologies for testing and evaluation of control software of autonomous systems.
Machine learning, reasoning and intelligence	AI: develop intelligent agents that can function in unstructured, open, complex and dynamic environments.
Science of Autonomy programme	Autonomy: conduct fundamental and multidisciplinary research into autonomy, with a focus on new teaming arrangements.
Unifying Inference through Attention	AI: develop a cognitive system that acquires strategies for controlling inference and that can develop new forms of reasoning about the world.
Mental Simulation as a Unifying Framework for Perception, Cognition and Control in Autonomous Systems and Dexterous Robots	Develop and demonstrate socially guided learning capabilities for autonomous systems that exploit mental simulation for the seamless integration of sensation, perception, cognition, active learning and control (part of the Science of Autonomy programme).
Understanding Satisficing in Human, Animal, and Engineered Autonomous Systems for Fast Decision Making	Develop a unified framework for fast satisficing (decision making to satisfy minimum requirements) with limited information (part of the Science of Autonomy programme).
Battlefield intelligence	
Automated Image Understanding Thrust	Computer vision: enhance high-level vision, namely, recognizing objects and activities, and inferring intentions and threats in surveillance imagery, as well as for semantic search of large image and video databases.
Human Mimetic Active Sonar Classification	Machine perception: develop algorithms, based on human perception of sound, for improved and automated active sonar classification.
Information Integration Thrust	Intelligence analysis: develop algorithms for data fusion, for finding relevant information in unstructured data, fuse data sets to find patterns of interest and understand the impact of this on decision making.
Mobile Autonomous Navy Teams for Information Surveillance and Search (MANTISS)	Collaborative autonomy: develop ways to control swarms and autonomous vehicles on navy subjects, such as search, reconnaissance and surveillance (part of the Machine Autonomy programme).
Organic Persistent Intelligence, Surveillance and Reconnaissance (OPISR)	Collaborative autonomy: combine a heterogeneous mix of manned and unmanned systems on ground patrol for intelligent intelligence, surveillance and reconnaissance (part of the Machine Autonomy programme).
Structured Machine Learning for Scene Understanding	Machine learning: develop mathematical models to enable machine learning without requiring precise structured models about the concept. This enables learning in dynamic new environments (part of the Machine Autonomy programme).
Undersea Signal Processing programme	Machine perception: develop signal processing algorithms for identifying and locating submarines.
Trinocular Structured Light System	Computer vision: develop a 3-D machine vision system that can detect small arms by shape.
Human–machine communication	
Semantic and Visual Representation of Autonomous System Perceptual Data for Effective Human/Machine Collaboration	Human–machine interaction: improve understanding of how to achieve cognitively compatible and shared semantic and visual representations of data, knowledge, and information collected by the autonomous system for both the human and the computer.

Name	Area of application/objective
3-D Audio-Cued Operator Performance Modeling	Human–machine interaction: research into how 3-D audio cues can improve attention for operators who are doing multiple tasks (with computers).
Chat Attention Management for Enhanced Situational Awareness	Natural language processing: develop algorithms that can learn and classify chat messages, summarize chat-room situations and give audio and visual cues to watchstanders.
Cognitive Robotics and Human Robot Interaction	Human–machine teaming: develop human-like representations, strategies and knowledge for cognitive robots, to enable better collaboration between machines and humans.
Damage Control for the 21st Century	Human–machine teaming: investigate human–machine collaboration though the use of a firefighting robot on ships.
Machine Classification of Spoken Language	Natural langage processing: classification and identification of the speech patterns of native and non-native speakers of English using phonetic and phonological analyses.
Command and control and collaborative autonomy	
Control Architecture for Robotic Agent Command and Sensing (CARACaS)	Collaborative autonomy: develop a control architecture add-on kit for swarms.
Adaptive Autonomy Controller	Human–machine teaming: improve human interaction with autonomous vehicles, allow decision making under diverse environments, work in communication denied environments.
Unmanned Air System Autonomy	Collaborative autonomy: conduct basic and applied research in autonomous control and collaborative control of unmanned aerial vehicles and heterogeneous naval teams.
Cognitively Inspired Decision Making for Visualization	Command and control of autonomous systems: investigate cognitive models for decision making to use in autonomous systems.
Goal Reasoning	Command and control of autonomous systems: research on identifying, explaining, and responding to unexpected situations that arise in the environment, independent of whether they imply an impending plan execution failure or a new opportunity to achieve goals of interest.
Swarm Control using Physicomimetics	Collaborative autonomy: swarm control based on a physics model where agents behave as point-mass particles and respond to artificial forces generated by local interactions with nearby particles.
Autonomy in unmanned systems	
Advanced Explosive Ordnance Disposal Robotic System (AEODRS)	Unmanned ground systems for explosive ordnance disposal: develop new generation of open, modular explosive ordnance disposal robots with autonomous navigation, manipulation and control behaviours.
Autonomous Aerial Cargo/ Utility System (AAUCS)	Unmanned aerial systems: develop autonomy for autonomous cargo drops and deliveries.
Biorobotics programme	Legged-robots: discover principles of locomotion and control from biological systems, to apply in engineering.
Covert Autonomous Disposable Aircraft (CICADA)	Unmanned aerial systems: develop swarm of small umanned aerial vehicles with gliding capabilities that can be deployed from aircraft for intelligence, surveillance and reconnaissance missions.
Flying-Swimmer (Flimmer) UAV/UUV	Unmanned maritime systems and unmanned aerial systems: develop unmanned systems capable of operating both in the air and in underwater environments.
Integrated Autonomy for Long Duration Operations	Unmanned systems in general: enable long-duration autonomy for unmanned vehicles.
Large Displacement Unmanned Undersea Vehicle- (LDUUV)	Unmanned maritime systems: develop unmanned underwater vehicles capable of long (70+ days) autonomous missions for intelligence, surveillance and reconnaissance purposes.

Name	Area of application/objective
Medium Displacement Unmanned Surface Vehicle (MDUSV)	Umanned maritime systems: develop unmanned surface vehicles capable of long autonomous missions for intelligence, surveillance and reconnaissance purposes.
Low-Cost UAV Swarming Technology (LOCUST)	Unmanned aerial systems: develop swarms of low-cost unmanned aerial vehicles to overwhelm enemy defences.
Robotic Touch Sensing, Manipulation, and Fault Detection	Robot manipulation: develop an artificial sensate skin for robots to extend the perceptual capabilities of robotic manipulators to include touch.

Source: Office for Naval Research, <http://www.onr.navy.mil/>.

II. United Kingdom

Table 4.6. Defence Science and Technology Lab

Name	Area of application/objective
General AI	
Autonomy for big data and defence	Machine learning: using autonomy for big data in various applications.
Exploiting tensors as a method for processing complex data on embedded processors	Hardware for machine learning: develop tensor units for processors.
Battlefield intelligence	
A novel technique for sensing underwater objects using coherence modulation acoustic speckle interferometry (CMASI)	Machine perception for underwater application: limited information available.
Autonomy in hazardous scene assessment	Computer vision: develop autonomous systems to assess scenes contaminated with hazardous materials.
A Bayesian Approach to Kill Assessment (BAKA)	Intelligence and targeting: limited information available.[a]
Coherent change detection for Polarimetric synthetic aperture radar (SAR)	Machine perception: limited information available.
Information processing and sense making	Machine learning for intelligence processing: improve information processing of a wide variety of formats and sources, for both unstructured and structured data. Enable automated hypothesis generation.
Multi-Source Analyst's Toolkit for Improved Spatio-Spectral Exploitation (Matisse)	Computer vision for intelligence analysis: improve registration (alignment of multiple images of an area), change detection (identifying potential changes between images of the same area) and object identification.
Persistent surveillance from the air	Machine perception: develop new sensor technologies for intelligence, surveillance and reconnaissance that can also use on/off-board processing technologies for auto-filtering and sensor communication.
Autonomy in unmanned systems	
Graduated response from unmanned novel technologies (GRUNT) standoff auto interdict and shadow with low-cost unmanned surface vessels	Unmanned maritime systems: limited information available.
Many drones make light work	Unmanned aerial systems: demonstrate and evaluate the benefit of swarms of unmanned aerial systems to defence.
Mimicking ants to develop capability of autonomous vehicles	Unmanned ground vehicles: use Ant Colony Optimization techniques to create optimal routes for autonomous vehicles.
Self-powered autonomous surface and underwater vehicles for persistent observation	Unmanned maritime systems: develop self-powered autonomous underwater vehicles, harvesting energy from the waves, to extend mission duration.

[a] Kill assessment is the evaluation of information to determine the result of a ballistic missile/re-entry vehicle intercept for the purpose of providing information for defence effectiveness and re-engagements.

Source: Defence Science and Technology Laboratory, <https://www.gov.uk/government/organisations/defence-science-and-technology-laboratory>.

III. European Union-funded projects

Table 4.7. European Defence Agency

Name	Area of application/objective
Battlefield intelligence	
Comprehensive Battlefield Identifcation (COBID)	AI for intelligence: develop battlefield identification systems.
Command and control and collaborative autonomy	
Technologies for multi-robots control in support of the soldier (MuRoC)	Command and control: develop technology to enable control of multiple robots in support of conventional troops.
Networked Multi-Robot Systems	Collaborative autonomy: develop a control system for swarm robots.
Autonomy in unmanned systems	
Semi-Autonomous Small Ground Vehicle, System Demonstrator (SAM-UGV)	Unmanned ground systems: develop small unmanned ground vehicles for patrol missions in urban terrain.
Technology Demonstration Study on Sense and Avoid Technologies For Long Endurance Unmanned Aerial Vehicles (LE-UAVs)	Computer vision: develop/improve sense-and-avoid technologies for unmanned aerial systems.
Unmanned Ground Systems Landscaping and Integration Study (UGS LIS)	Unmanned ground systems: develop common operational requirements for unmanned ground systems.
Unmanned Ground Tactical Vehicle (UGTV)	Unmanned ground systems: develop automatic control of ground vehicles for intelligence surveillance and reconnaissance, patrolling, minesweeping, engineering and transport.
Transportable Autonomous Patrol for Land Border Surveillance System (TALOS)	Unmanned ground systems: develop an autonomous unmanned ground vehicle for border surveillance.

Source: European Defence Agency, Research and Technology, <https://www.eda.europa.eu/what-we-do/eda-priorities/research-technology>.

IV. India

Table 4.8. Defence Research Development Organization

Name	Area of application/objective
General AI	
AI Techniques for Net Centric Operations (AINCO)	AI for intelligence processing: develop a suite of technologies for creation of knowledge base, semantic information reception and handling, inference reasoning, and event correlation.
Command and control and collaborative autonomy	
Knowledge Resources and Intelligent Decision Analysis (KRIDA)	AI for command and control: develop a system that aims to achieve the management of large-scale military moves using extensive knowledge base and data handling.
Autonomy in unmanned systems	
Autonomous Unmanned Research Aircraft	Unmanned aerial systems: develop an autonomous unmanned combat aerial vehicle: limited information available.
RoboSen	Unmanned ground systems: develop a mobile robot system capable of autonomous navigation in semi-structured environments with obstacle avoidance capability and continuous video feedback.

Source: Centre for Artificial Intelligence and Robotics, Defence Research and Development Organization, <http://www.drdo.gov.in/drdo/labs/CAIR/English/index.jsp?pg=homebody.jsp>.

V. Japan

Table 4.9. Acquisition, Technology and Logistics Agency

Name	Area of application/objective
Battlefield Intelligence	
Radio Frequency (RF) Imaging Guidance Technology	Computer vision: develop radio frequency (RF) imaging guidance technology with sophisticated signal processing techniques to achieve a much higher resolution, and to enable detection and tracking of stationary low radar cross section targets such as future stealthy vessels and ground targets, which are difficult to detect and track with conventional RF seeker technology. It will utilize information from external sensors, target selection by map matching, clutter suppression etc.
Sonar System for Next-Generation Submarines	Target detection in underwater environment: develop and implement sensing and signal-processing technologies for submarines, enhancing the capability to detect targets and respond to acoustic features in shallow-water environments.
Human–machine communication	
Human System Technology	Human-computer interfaces: develop technology that enables information sharing in a combat operation. The objective is to study the hands-free and eyes-free operation of information devices via See-through Head Mounted Display and speech recognition.
Command and control and collaborative autonomy	
Remote Control of Several Miniature Vehicles	Command and control: design remote control for swarms of miniature vehicles for reconnaissance in urban areas.
Autonomy in unmanned systems	
Unmanned Aerial Research System	Unmanned aerial systems: develop an air-launched medium-sized, unmanned aerial vehicle featuring pre-programmed autonomous flight and landing for reconnaissance and other missions.
Unmanned Ground Vehicle (UGV)	Unmanned ground systems: research on a high-speed, unmanned ground vehicle, which could be operated by a combination of a remote control and an autonomous obstacle avoidance technology based on Lidar (a surveying method using laser light).

Source: Acquisition, Technology and Logistics Agency, <http://www.mod.go.jp/atla/en/kousouken.html>.

VI. Russia

Table 4.10. Russian Foundation for Advanced Research Projects

Name	Area of application/objective
General AI	
UNICUM	AI: develop a common underlying technology to provide artificial intelligence to a plethora of unmanned systems.
Battlefield intelligence	
Intelligent analysis of unmanned aerial vehicle (UAV) imagery	Computer vision: improve intelligent object recognition and classification of imagery captured by unmanned aerial systems during intelligence, surveillance and reconnaissance missions.
Human–machine communication	
Facial Recognition Technology	Computer vision: enable facial recognition techniques under difficult conditions.
Autonomy in unmanned Systems	
Nerehta	Unmanned ground systems: develop a modular unmanned ground combat vehicles.
Rotary-winged unmanned air vehicle testbed	Unmanned aerial systems: create a 'flying laboratory' unmanned aerial vehicle, which will explore complex, multidisciplinary technologies necessary to advance autonomous flight.
Avatar	Humanoid robot: develop an autonomous humanoid robot that could be used as an avatar to control unmanned systems.
Lynx	Unmanned ground systems: develop a robot mule that could be used for carrying supplies in the field.

Source: Russian Foundation for Advanced Research Projects, <http://fpi.gov.ru/>.

Appendix C: Sample of companies developing autonomous weapon systems as defined by the International Committee of the Red Cross[1]

Table 5. Sample of companies developing autonomous weapon systems

Type	Subtype	Key companies	Examples
Missile and rocket defence weapons		CPMIEC (China)	HQ-9
		713th Research Institute (China)	Type 730, Type 1130 CIWS
		Rheinmetall (Germany)	Nächstbereichschutzsystem (NBS) MANTIS
		MBDA (Trans-European)	EMADS, MICA, Spada 2000, MEADS, FLAADS
		IAI (Israel)	Arrow 2, Arrow 3, Spyder
		Rafael (Israel)	Arrow 2, Arrow 3, Spyder
		MBDA/Thales/EUROSAM (Italy/France)	Aster
		Mitsubishi (Japan)	Type 3 chū-sam
		Thales (Netherlands)	Goalkeeper
		Hanwha Defence Systems (South Korea)	K30 Biho
		Almaz-Antey (Russia)	Tor, S-400, S-300
		KBP Instrument Design Bureau (Russia)	Kashtan, Pantsir S1, AK-630
		Saab (Sweden)	Bamse
		Kratos (USA)	AN/SEQ-3 Laser Weapon System
		Lockheed Martin (USA)	Aegis, THAAD
		Raytheon (USA)	Patriot, Phalanx, SeaRAM, C-RAM
Active protection systems		Norinco (China)	GL-5
		EADS, Rheinmetall, KMW (Germany)	MUSS
		Rheinmetall (Germany)	AMAP-ADS
		Thales (France)	Shark
		IAI (Israel)	Trophy
		IMI (Israel)	Iron Fist
		Rafael (Israel)	Trench Coat, Trophy
		Oto Melara (Italy)	Scudo Active Defence System (ADS)

Type	Subtype	Key companies	Examples
		KBP Instrument Design Bureau (Russia)	Arena, Drozd
		NII Transmash (Russia)	Shtora
		Microtek (Ukraine)	Zaslon, Varta
		Artis (USA)	Iron Curtain
		Raytheon (USA)	Quick Kill
		Saab (South Africa)	LEDS-150
Anti-personnel 'sentry' weapons		G-Nius (Israel)	Guardium, AvantGuard, HMV
		Rafael (Israel)	Sentry Tech
		Samsung (South Korea)	SGR-A1
		DoDAAM (South Korea)	aEgis, Super aEgis
		General Dynamics (USA)	MDARS-E
		Izhevsk Radio Plant (Russia)	Mobile Robotic Complex
		OPK (Russia)	Inteltеha
Munitions	Sensor-fused munitions	Nexter (France)	BONUS 155mm
		GIWS mbh (Germany)	SMArt 155mm
		Rafael (Israel)	SPICE
		Saab Bofors (Sweden)	STRIX 120mm, BONUS 155mm
		NESCOM (Pakistan)	H-2 SOW, H-4 SOW
		Tactical Missiles Corporation (Russia)	KAB-500-SE
		Boeing (USA)	GBU-39 Small Diameter Bomb (SDB)
		Raytheon (USA)	M982 Excalibur 155mm
	Missiles	CHETA (China)	C-802
		MBDA (Trans-European)	CVS302 Hoplite, Brimstone, Meteor, Exocet
		BrahMos (India/Russia)	BrahMos
		Rafael (Israel)	Spike anti-tank guided missile
		Kongsberg (Norway)	Naval Strike Missile
		Vympel (Russia)	R-77
		Roketsan (Turkey)	SOM Cruise Missile

Type	Subtype	Key companies	Examples
		Lockheed Martin (USA)	Nemesis, LRASM
		Raytheon (USA)	AIM-120 AMRAAM
	Loitering munitions	CASC (China)	CH-901
		MBDA (Trans-European)	Caelus, Tiger, Fire Shadow
		Rheinmetall (Germany)	TARES, TAIFUN
		AeroEnvironment (Israel)	Switchblade
		Elbit (Israel)	SkyStriker
		IAI (Israel)	Harpy, Harpy NG, Harop, Green Dragon, Rotem
		UVision (Israel)	Hero, Blade Arrow
		WB Electronics (Poland)	Warmate
		Korea Aerospace Industries (South Korea)	Devil Killer
		Lockheed Martin (USA)	Terminator
		Textron Systems (USA)	Battlehawk, T-RAM
Torpedoes and encapsulated torpedo mines		710 Research Institute (China)	EM-52, EM-11, EM-53
		Eurotorp (France/Italy)	MU90/IMPACT Advanced Lightweight Torpedo
		RWM (Italy)	MR-80, MP-80, Murena, Manta
		WASS (Italy)	Black Shark
		. . (Russia)	PMK-2 encapsulated torpedo mine
		. . (Russia)	MDM, MSHM
		BAE Systems (UK)	Sea Urchin
		Alliant Techsystems (USA)	MK 60 CAPTOR Encapsulated Torpedo
		Gould, Inc (USA)	MK 48 Heavyweight Torpedo

. . = not available or not applicable

Source: SIPRI data set on autonomy in weapon systems.

[1] The systems listed in table 5 are those that may be classified as 'autonomous' according to the definition provided by the International Committee of the Red Cross (ICRC) (i.e. 'autonomous weapon systems' are weapons that are capable of independently selecting and attacking targets without human intervention). See International Committee of the Red Cross, *Autonomous Weapon Systems: Technical, Military, Legal and Humanitarian Aspects*, Expert Meeting Report (ICRC: Geneva, 2014). It should be stressed that the table is not intended to provide a comprehensive picture of the existing systems nor the companies that develop them.

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