AUTONOMOUS WEAPONS: THE FUTURE BEHIND US

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ABSTRACT

AUTONOMOUS WEAPONS: THE FUTURE BEHIND US, by Major Matthew Freeman Noyes, 103 pages.

Militaries have long used weapons with varying degrees of autonomy. However, recent technology advances have made possible more capable autonomous weapons, sparking calls by civil society groups and discussions in the United Nations (UN) on banning autonomous weapons. This thesis identifies potential military uses of autonomous weapons and makes prediction on their use through 2030. This is accomplished by analyzing past and present uses of autonomous weapons, ongoing technology developments, and developing an ontology for defining and describe autonomous weapons.

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ACRONYMS

AI	Artificial Intelligence
AMRAAM	Advanced Medium-Range Air-to-Air Missile
CCW	Convention on Certain Conventional Weapons
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
DoDD	Department of Defense Directive
Harpy NG	Harpy Next Generation
IMU	Inertial Measurement Units
MEMS	Microelectromechanical Systems
SIPRI	Stockholm International Peace Research Institute
UN	United Nations
UK	United Kingdom
US	United States of America

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CHAPTER 1

INTRODUCTION

> While today we have flying drones, tomorrow's battlefields will be filled with walking, crawling, jumping, and flying robots. In the near future it is possible a fully robotized unit will be created, capable of independently conducting military operations. How shall we fight under such conditions? What forms and means should be used against a robotized enemy? What sort of robots do we need and how can they be developed? Already today our military minds must be thinking about these questions.
>
> — Valery Gerasimov, "The Value of Science is in the Foresight"

Rapid advancements in robotics and artificial intelligence (AI) have brought the prospect of autonomous weapons to the forefront as a priority international security issue. This issue was highlighted by Secretary General António Guterres, in his 2018 address to the United Nations General Assembly, when he said, "The prospect of weapons that can select and attack a target on their own raises multiple alarms—and could trigger new arms races."[1] While science fiction stories and works by advocacy groups[2] illustrate various dystopian futures involving autonomous weapons, militaries are continuing to invest in developing autonomous weapons. Understanding how autonomous weapons are likely to be used is critical to assessing the future security environment, to considering various policy options currently debated within governments and in intergovernmental fora, and to take appropriate action to improve international security and stability. This

[1] António Guterres, "Address to the General Assembly," Transcript, 25 September 2018, accessed 26 October 2018, https://www.un.org/sg/en/content/sg/speeches/2018-09-25/address-73rd-general-assembly.

[2] For example, The Campaign to Stop Killer Robots, https://www.stopkillerrobots.org/call-to-action/; The Future of Life Institute, https://futureoflife.org.

thesis seeks to develop this requisite understanding of the future security environment through considering the potential military uses of autonomous weapons through 2030.

Militaries have long used various forms of autonomous weapons—things that are designed or used to cause harm in reaction to sensory inputs with minimal control of a user. Traps and mines are an early form of autonomous weapons and use of canines and self-propagating biological agents to cause harm could also be categorized as autonomous weapons. For nearly one hundred years, limited autonomy has been a key feature of air and missile defense systems (e.g. Patriot, Aegis, Kashtan, and MK Phalanx systems), and militaries have used proximity fused and homing munitions since World War II.

Modern militaries currently use fire-and-forget missiles, like the AIM-120 Advanced Medium-Range Air-to-Air Missile (AMRAAM), to engage targets beyond the line of sight of their operators. Militaries are increasingly using armed remotely operated aerial vehicles, which routinely incorporate autonomous navigation, and equipping their ground vehicles with active protection systems (e.g. AMAP-ADS, DROZD, and Trophy systems). Meanwhile, the commercial automotive industry appears to be within a few years of delivering autonomous driving.[3] Ongoing advances in robotics, computing, and AI, coupled with the stated and demonstrated research priorities of major military powers, suggest that militaries may be on the verge of employing advanced autonomous weapon system that displace, rather than just augment, manned weapon systems.

[3] McKinsey Center for the Future of Mobility, "Autonomous Driving," McKinsey and Company, accessed 24 April 2019, https://www.mckinsey.com/features/mckinsey-center-for-future-mobility/overview/autonomous-driving.

This thesis focuses on a pragmatic assessment of the potential future military uses of autonomous weapons over the period 2019 to 2030. This assessment is intended to complement existing literature which predominately focuses on three areas: (1) normative issues (which are particularly relevant for ongoing discussions in the United Nations (UN) Convention on Certain Conventional Weapons (CCW); (2) United States of America (US) military acquisitions challenges; and (3) broader assessments of the likely impact of AI advances on society where military use of autonomous weapons is just one aspect amongst several considered.

Defining Autonomous Weapons

This thesis uses "autonomous weapons" broadly to refer to things designed or used to cause harm through independent actions taken in response to sensing attributes of a target. This builds on the common definition of "weapon" as "a thing designed or used for inflicting bodily harm or physical damage."[4] Definitions of "autonomous" vary substantially,[5] but this thesis uses "autonomous" to broadly describe things that independently take action in response to sensory inputs. For example, the common household thermostat is a simple autonomous system—turning on, or off, air conditioning based upon the temperature (typically detected and controlled by the expansion and contraction of a bimetallic coil).

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[4] *Oxford English Dictionary*, s.v. "weapon," accessed 11 October 2018, https://en.oxforddictionaries.com/definition/weapon.

[5] For further discussion see the literature review chapter.

In adopting this definition, this thesis provides an alternative approach from those used by some authors—specifically departing from attempts to distinguish between automatic and autonomous based AI or other ambiguous descriptions of the complexity of computation. The literature review chapter include a brief discussion on alternative definitions and distinctions, and the ontology section in the analysis chapter further develops the approach to defining autonomous weapons used in this thesis.

Primary Research Question

The primary question this thesis seeks to answer is: Through 2030, what are the likely potential military uses of autonomous weapons? This thesis answers this question by analyzing historic and contemporary uses of weapons with varying degrees of autonomy and considering a range of academic literature and the contemporary statements and actions of various governmental, commercial organizations, and advocacy groups related to autonomous technologies. To provide for falsifiability, this thesis makes specific predictions for the likely development, adoption, and use of autonomous weapons over the next ten years based upon supporting models for describing and considering autonomous weapon systems.

Secondary Questions

This thesis also considers several secondary questions, including:

1. What are the key components of autonomous weapons?

2. How should autonomous weapons be assessed?

3. What are the advantages of autonomous weapons?

4. What are the potential techniques to counter and protected against autonomous weapons?
5. What is the likely path of innovation and adoption of autonomous weapons?

Delimitation

This work does not consider potential ethical, policy, and legal concerns, along with potential resulting constraints, to the development and use of autonomous weapons. There is robust ongoing debate on these subjects, including twenty-eight countries calling for a prohibition of fully autonomous weapons.[6] While these are important and interesting subjects, this work focuses on the potential military uses absent the implementation of such constraints. This is in recognition of a range factors, including three primary considerations: the challenge of effective arms control agreements; the need for ex ante forecasts to inform consideration of potential policy or legal constraints; and to serve as a complement to existing literature focused on normative and ethical aspects.[7]

This delimitation is reasonable due to the competitive and chaotic nature of the international system. Establishing effective arms control regimes is a significant

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[6] Campaign to Stop Killer Robots, "Country Views on Killer Robots," 22 November 2018, accessed 23 January 2019, https://www.stopkillerrobots.org/wp-content/uploads/2018/11/KRC_CountryViews22Nov2018.pdf.

[7] See, for example: Kenneth Anderson, and Matthew C. Waxman, "Debating Autonomous Weapon Systems, Their Ethics, and Their Regulation Under International Law, in *The Oxford Handbook of Law, Regulation, and Technology*, eds. Roger Brownsword, Eloise Scotford, and Karen Yeung (New York: Oxford University Press, July 2017), Chapter 45, accessed 23 January 2018, https://ssrn.com/abstract=2978359.

challenge; national interests and military effectiveness is often the foremost concern in conflict, presenting the risk that agreements may collapse in the event of war.[8] Moreover, absent demonstrated examples of the harms of a particular weapon, as was the case with land mines and chemical weapons, it is unclear whether there is sufficient political motivation to adopt an arms control agreement. Even for existing military capabilities, like offensive cyber operations, twenty years of UN discussions have resulted in only limited progress in establishing constraints on state use.[9]

Beyond the first order policy question of whether there should be policy or legal constraints on the development or use of autonomous weapons, developing specific technical, verifiable, and enforceable measures to constrain development or adoption of autonomous weapons is a substantial challenge. Such an effort ought to be informed by an ex ante assessment of what is likely to exist absent such a constraint being adopted, to enable subsequent assessment of the effectiveness of a control regime. Therefore, this work limits the scope of the analysis to likely potential military uses of autonomous weapons in the absence of effective ethical, policy, or legal constraints.

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[8] Colin Gray, *House of Cards: Why Arms Control Must Fail* (Ithaca, NY: Cornell University Press, 1992).

[9] Elaine Korzak, "UN GGE on Cybersecurity: The End of an Era?" *The Diplomat*, 31 July 2017, accessed 19 February 2019, https://thediplomat.com/2017/07/un-gge-on-cybersecurity-have-china-and-russia-just-made-cyberspace-less-safe/.

CHAPTER 2

LITERATURE REVIEW

> Preparation for war is an expensive, burdensome business, yet there is one important part of it that costs little—study. However changed and strange the new conditions of war may be, not only generals, but politicians and ordinary citizens, may find there is much to be learned from the past that can be applied to the future and, in their search for it, that some campaigns have more than others foreshadowed the coming pattern of modern war.
>
> — Field Marshall Slim, *Defeat into Victory*

There is a rapidly growing range of literature that considers the international security implications of AI. However, there is limited scholarship that focuses specifically on how militaries are likely to use autonomous weapons through 2030. Existing literature is presented in four categories. First, literature related to the UN CCW meetings on lethal autonomous weapons systems. Second, assessments of the likely impacts to society from AI and use of increasingly autonomous systems, where use by militaries in weapons is one amongst many elements considered. Third, various national government strategies, plans, policies, and statements related to autonomy, AI, and military applications. Fourth, literature on prediction in the national security context.

Existing literature predominately focuses on United States and Western European perspectives and the activities of these military and associated military industries in the development of increasingly autonomous weapons due both to availability of information and relative size on arms industry. While this thesis includes examples of autonomous weapons from a range of states, and even non-state actors, there is limited information available on how numerous countries are currently approaching autonomous weapons, particularly outside of the United States and Western Europe.

The lack of broader internationally representative data and literature is a weakness. However, it is reasonable to consider the United States as indicative of broader military trends due to the scale of US military arms sales, the size of the US military, and total US research and development investments in relevant research areas. The Stockholm International Peace Research Institute (SIPRI) list of the top one hundred arms-producing and military service companies identifies forty-two as being US companies.[10] These US companies constitute 57 percent of the sales by the top one hundred companies.[11] The next closest are Russia at 9.5 percent, U.K at 9 percent, and France at 5.3 percent.[12] The US military expenditure is estimated to be over one-third of total world expenditure, and total NATO expenditure is estimated to be over 50 percent.[13] Additionally, the United States remains the largest investor in research and development amongst Organisation for Economic Cooperation and Development countries,[14] and,

[10] Aude Fleurant, Alexandra Kuimova. Nan Tian, Pieter D. Wezeman, and Siemon T. Wezeman, "The SIPRI Top 100 Arms-Producing and Military Services Companies, 2017" (Fact Sheet, Stockholm International Peace Research Institute, December 2018), accessed 25 February 2019, https://www.sipri.org/publications/2018/sipri-fact-sheets/sipri-top-100-arms-producing-and-military-services-companies-2017.

[11] Ibid., 2.

[12] Ibid., 3.

[13] International Institute for Strategic Studies, *The Military Balance 2019* (New York: Routledge, 2019).

[14] Organisation for Economic Cooperation and Development, "Research and Development Statistics," July 2018, accessed 25 February 2019, http://www.oecd.org/innovation/inno/researchanddevelopmentstatisticsrds.htm.

since the 1950s, the United States has led in research and development of AI[15]—though it must be noted China is investing heavily in AI research.[16] Given these factors, and in the absence of more internationally representative literature and data, general inferences on military trends can reasonably be made from the available data, despite it being predominately focused on developments in the United States and Western Europe.

Literature Related to UN CCW Meetings on Lethal Autonomous Weapons Systems

Civil society organizations, notably the Campaign to Stop Killer Robots[17] and the Future of Life Institute,[18] have raised normative and ethical concerns regarding autonomous weapons and advocated for a preemptive ban on fully autonomous weapons. In November 2013, substantially in reaction to these concerns being expressed by member states, the High Contracting Parties to the CCW adopted a report that directed:

> the Chairperson will convene in 2014 a four-day informal Meeting of Experts, from 13 to 16 May 2014, to discuss the questions related to emerging technologies in the area of lethal autonomous weapons systems, in the context of the objectives and purposes of the Convention. He will, under his own

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[15] Vincent Boulanin and Maaike Verbruggen, "Mapping the Development of Autonomy in Weapon Systems" (Report, Stockholm International Peace Research Institute, 2017), 94, accessed 30 October 2018, https://www.sipri.org/publications/2017/other-publications/mapping-development-autonomy-weapon-systems.

[16] Kai-Fu Lee, *AI Superpowers: China, Silicon Valley, and the New World Order* (Boston, MA: Houghton Mifflin Farcourt, 2018).

[17] Campaign to Stop Killer Robots, "About Us," accessed 15 November 2018, https://www.stopkillerrobots.org/about-us/.

[18] The Future of Life Institute, "National and International AI Strategies: A Global Landscape," accessed 15 November 2018, https://futureoflife.org/ai-policy/.

> responsibility, submit a report to the 2014 Meeting of the High Contracting Parties to the Convention, objectively reflecting the discussions held.[19]

The UN CCW has since held meetings to discuss lethal autonomous weapon systems each year from 2014 to 2018. Over 500 statements, papers, and presentations from these meetings are publicly available on the UN Office of Geneva website.[20] These documents cover a wide range of topics, including government positions, ontological frameworks for describing technologies, overviews of existing systems with autonomy, legal issues, ethical issues, and a few presentations focused on military affairs.

The work in the UN CCW also appears to have motivated the work of various researchers seeking to inform discussions within the UN Group of Governmental Experts. Particularly notable is Vincent Boulanin and Maaike Verbruggen's November 2017 report on the development and use of autonomy in weapon systems. Their report provides a broad overview of what are autonomous weapons, the current state of autonomy in weapon systems, an assessment of the drivers and impediments to developing autonomous weapons, and identification of the key locations and entities driving

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[19] As of 14 November 2018, there are 125 state parties to the Convention on Certain Conventional Weapons. See, The United Nations Office at Geneva, "High Contracting Parties and Signatories," accessed 15 November 2018, https://www.unog.ch/80256EE600585943/(httpPages)/3CE7CFC0AA4A7548C12571C00039CB0C?OpenDocument.

[20] United Nations Office at Geneva, "Background on Lethal Autonomous Weapons Systems in the CCW," accessed 15 November 2018, https://www.unog.ch/80256EE600585943/(httpPages)/8FA3C2562A60FF81C1257CE600393DF6?OpenDocument.

innovation advancing autonomy.[21] This thesis builds on these existing works in three primary ways:

1. Making predictions on future military use of autonomous weapons, rather than focusing primarily on past and present uses.
2. Expanding the consideration of autonomous weapons—from focusing on systems involving advanced computation to systems that react to sensory inputs without direct user control. This change in scope both expands the evidentiary basis for making predictions, while providing a clearer distinction for defining autonomous weapons.
3. Exploring the vulnerabilities to remotely operated systems which may be a key driving force of increased autonomy.

Broader Assessments on Security Implications of Artificial Intelligence

There is also a growing range of literature considering various security implications of AI, where autonomous weapons are part of a broader assessment. Two notable books on this subject are Paul Scharre's *Army of None* and David Hambling's *Swarm Troopers*. Scharre's book provides a broad introduction to autonomous weapons, their ongoing development and use, and the potential implications to war.[22] Scharre has worked substantially on this subject, in both the UN CCW's processes on autonomous

[21] Boulanin and Verbruggen, "Mapping the Development of Autonomy in Weapons Systems."

[22] Paul Scharre, *Army of None: Autonomous Weapons and the Future of War* (New York: W. W. Norton and Company, 2018).

weapons and worked on the subject while employed in the Office of the Secretary of Defense. Hambling's *Swarm Troopers* provides detailed information on use of autonomy in military aviation from World War I to the present, while predicting future use of autonomy in military aviation.[23] This thesis builds upon their works by apply several of the frameworks developed by Scharre, while extend Hambling's approach of looking at historical use of autonomous systems to consider use of autonomy in other domains.

In *Artificial Intelligence, International Competition, and the Balance of Power,* Michael Horowitz persuasively describes the potential disruptive impacts of AI to international security and the character of war.[24] Other authors[25] have reached conclusions similar to Horowitz on the potential for AI to have a transformative impact on military affairs and international security. Works like Horowitz's considers the implications of military use of autonomous weapons amongst a range of other effects, such as economic gains and labor disruptions, and potential competitive advantages of various countries as early adopters of AI. In contrast to these broader evaluations, this

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[23] David Hambling, *Swarm Troopers: How Small Drones Will Conquer the World* (Venice, FL: Archangel Ink, 2015).

[24] Michael C. Horowitz, "Artificial Intelligence, International Competition, and the Balance of Power," *Texas National Security Review* 1, no. 3 (May 2018): 36-57, accessed 15 November 2018, https://tnsr.org/2018/05/artificial-intelligence-international-competition-and-the-balance-of-power/.

[25] Greg Allen and Taniel Chan, "Artificial Intelligence and National Security" (Belfer Center, Harvard Kennedy School, Cambridge, MA, July 2018), accessed 16 October 2018, https://www.belfercenter.org/sites/default/files/files/publication /AI%20NatSec%20-%20final.pdf; Darrell M. West and John R. Allen, "How Artificial Intelligence is Transforming the World" (Report, Brookings Institute*,* 24 April 2018), accessed 16 October 2018, https://www.brookings.edu/research/how-artificial-intelligence-is-transforming-the-world/.

thesis focuses on the narrow question of the potential military applications of autonomous weapons through 2030.

Finally, a range of authors have written recently on the potential for AI to impact various areas of national security. Jim Baker, former general counsel of the Federal Bureau of Investigation, published a four-part series on the counterintelligence implications of AI for the United States.[26] Additionally, at least a dozen authors, including six graduates of the US Army Command and General Staff College, have written on potential military applications of autonomous weapons, developed specific proposals for how the US military could use autonomous systems, or analyzed US Department of Defense challenges in acquiring autonomous systems. Unlike these works, this thesis seeks to ask the general question of the potential military use of autonomous weapons through 2030, rather than questions specific to the US military on developing, acquiring, and using autonomous weapons.[27]

Government and Industry Publications

The third set of literature this thesis substantially builds upon is government statements on autonomy and AI. The US Department of Defense has published several policies, studies, and statements related to autonomy. Particularly noteworthy is

[26] Jim Baker, "Artificial Intelligence–A Counterintelligence Perspective: Part IV," Lawfare, 29 October 2018, accessed 15 November 2018, https://www.lawfareblog.com /artificial-intelligence-%E2%80%93-counterintelligence-perspective-part-iv.

[27] However, the US is certainly a significant subject of analysis in this thesis given the substantial ongoing research and development of autonomy occurring in the United States and being funded by the US government.

Department of Defense Directive (DoDD) 3000.09, *Autonomy in Weapon Systems,* which sets forth a Department of Defense (DoD) policy that "[a]utonomous and semi-autonomous weapon systems shall be designed to allow commanders and operators to exercise appropriate levels of human judgment over the use of force."[28] However, DoD is not shying away from developing autonomous weapons; for example, DoD publishes an *Unmanned Systems Integrated Roadmap*, which substantially emphasizes a future role of weaponized autonomous systems in the US military.[29] A November 2018, Congressional Research Service report provides an excellent overview of these efforts, and others, related to US military development of autonomous systems.[30] More recently, on 17 April 2019 the US Air Force published its Science and Technology strategy, which emphasizes the role of autonomy improving the speed, resilience, mass, and effectiveness of weapon systems.[31]

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[28] Department of Defense, Department of Defense Directive (DoDD) 3000.09, *Autonomy in Weapons Systems*, C1 (Washington, DC: Government Printing Office, May 2017).

[29] Department of Defense*, Unmanned Systems Integrated Roadmap 2017-2042* (Washington, DC: Government Printing Office, 2018), 22, accessed 15 November 2018, https://assets.documentcloud.org/documents/4801652/UAS-2018-Roadmap-1.pdf.

[30] Andrew Feickert, Jennifer K. Elsea, Lawrence Kapp, and Laurie A. Harris, *U.S. Ground Forces Robotics and Autonomous Systems (RAS) and Artificial Intelligence (AI)* (Washington, DC: Congressional Research Service, November 2018), accessed 15 November 2018, https://fas.org/sgp/crs/weapons/R45392.pdf.

[31] US Air Force, "Science and Technology Strategy: Strengthening USAF Science and Technology for 2030 and Beyond," April 2019, accessed 25 April 2019, https://www.af.mil/News/Article-Display/Article/1816965/new-air-force-science-technology-strategy-puts-focus-on-speed/.

Additionally, there are several ongoing acquisitions-related activities relevant to autonomy in weapon systems. For example, in 2018, United Kingdom (UK) Army held "Exercise Autonomous Warrior"[32] and in March 2019 the US Army hosted an industry day for its Advanced Targeting and Lethality Automated System Program.[33] While much of the information available from these, and related events, are proprietary or otherwise not publicly available, these events did provide some public information on current acquisition efforts these militaries are pursuing along with the related research and development being performed in defense industries. This work does not focus on particular acquisition efforts, or the challenges particular military organizations face in this regard; rather, the focus is on abstracting from these ongoing efforts to predict generally how militaries are likely to use autonomous weapons through 2030.

Prediction in National Security

Finally, Richard Danzig's "Driving in the Dark: Ten Propositions About Prediction and National Security" substantially informs the methodology of this thesis.[34] Danzig highlights the fallibility of social science predictions, the negative impact when

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[32] Ministry of Defense, "Army Innovation: Exercise Autonomous Warrior," accessed 6 April 2019, https://www.army.mod.uk/news-and-events/events/awe-2018/.

[33] Army Contracting Command, "Industry Day for the Advanced Targeting and Lethality Automated System (ATLAS) Program," Federal Businesss Opportunities, 22 February 2019, accessed 6 April 2019, "https://www.fbo.gov/index.php?s=opportunity &mode=form&tab=core&id=6b5d5aeb584c667d4e6f5103bf6acac6&_cview=0.

[34] Richard Danzig, "Driving in the Dark: Ten Propositions About Prediction and National Security" (Paper Center for New American Security, Washington, DC, October 2011), accessed 15 October 2018, https://www.cnas.org/publications/reports/driving-in-the-dark-ten-propositions-about-prediction-and-national-security.

these predictions are used to shape planning, and the propensity of DoD to rely upon such predictions to its own detriment. Danzig's work is an apt critique of DoD's propensity for prediction, particularly as it affects DoD's lengthy acquisitions process.

Nevertheless, this thesis makes predictions. These predictions are made in order to provide for falsifiability of the supporting models and analysis, in order to enable future revisions as additional information becomes available. As such, the predictions should not be used as high confidence assumptions about the future, but at the basis for anticipating and adapting to future circumstances. This thesis does not make recommendations specific to DoD and its efforts to acquire and use autonomous weapons; rather, it focuses on the general question of how militaries will potentially use autonomous weapons through 2030. Danzig's caution about prediction as the basis in planning and acquisition processes is well founded; however, predictions also enable the adaptability, Danzig seeks to encourage, by anticipating future circumstances and identifying factors likely to drive changes.

CHAPTER 3

RESEARCH METHODOLOGY

> [T]he greatest value of my invention will result from its effect upon warfare and armaments, for by reason of its certain and unlimited destructiveness it will tend to bring about and maintain permanent peace amongst nations.
>
> — Nikola Tesla, "Method of and Apparatus for Controlling Mechanism of Moving Vessels or Vehicles"

This thesis seeks to identify how military are likely to use autonomous weapons through multiple qualitative analytic assessments. Each of these perspectives were informed by analysis of relevant literature, government statements, and industry and scientific reports on existing technologies and research projects. In particular, the analysis was substantially informed by numerous industry responses to the US Army Industry Day for the Advanced Targeting and Lethality Automated System Program,[35] including over 20 industry briefings attended by the author. Additionally, the limited reports from the British Army's Exercise Autonomous Warrior were reviewed. [36] However, this thesis relies only on unclassified public data, forgoing any use of proprietary or otherwise restricted information from these events.

The first analytic perspective focuses on the ontology for defining and distinguishing autonomous weapons and identifying their key components. Current literature involves substantial ambiguity in defining autonomy, which this perspective

[35] Army Contracting Command, "Industry Day for the Advanced Targeting and Lethality Automated System (ATLAS) Program."

[36] Ministry of Defense, "Army Innovation Exercise Autonomous Warrior."

seeks to improve upon by directly considering the ontology, that is the set of concepts and relationships between those concepts,[37] used to define and describe autonomous weapons. This perspective considers existing distinctions between weapons that have various automated functions, to more precisely define autonomous weapons. This analysis seeks to answer threshold questions of what autonomous weapons are, both in distinguishing them from other things and developing a descriptive systems model for identifying the key components of an autonomous weapon, which is used to frame subsequent analysis.

The second analysis focuses on past, present, and future use by militaries of weapons that exhibit various degrees of autonomy. This analysis is conducted for each of the five domains recognized by US military doctrine (air, land, maritime, space, and cyberspace)[38] using historic examples, current weapon systems, and published statements, policies, strategies, plans, and research priorities of various nations and militaries. The age of historical examples of autonomous weapons vary by domain, cyberspace considers examples primarily from the late 1980s to present, space from 1960s to present, air from the 19th century to present, and examples used for the land and sea domain stretch much further into the past in considering mines and traps as informative of potential military uses of autonomous weapons. This analysis provides an

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[37] Thomas R. Gruber, "Toward Principles for the Design of Ontologies used for Knowledge Sharing" (Presented at the Padua workshop on Formal Ontology, March 1993), later published in *International Journal of Human-Computer Studies* 43, no. 4-5 (November 1995): 907-928, accessed 22 April 2019, http://tomgruber.org/writing/onto-design.pdf.

[38] Joint Chiefs of Staff, Joint Publication 3-0, *Joint Operations* (Washington, DC: Government Printing Office, 2017).

empirical basis for identifying how militaries have used and are likely to use of autonomous weapons through 2030.

The third analytic perspective focuses on the technologies that enable autonomous weapons. This perspective abstracts from the empirical basis used in the second analysis and considers each of the six descriptive factors developed in the systems model from the ontological analysis to identify the key technology factors relevant to the development, capabilities, and vulnerabilities of autonomous weapons. This perspective assesses reports from a range of sources on ongoing research and development of related technologies, such as machines learning, autonomous vehicles, and robotics. This perspective also considers potential adversarial counter-measures to remotely operated and autonomous weapons to develop predictions on likely evolutionary trajectory of military use of autonomous weapons.

Based on these three analytic perspectives, this thesis seeks to identify likely potential military uses of autonomous weapons through 2030. The thesis concludes with predictions related to development and use of autonomous weapons, recommending approaches for further study of the subject, and identifying questions for further research.

Long-term predictions on societal changes are consistently inaccurate.[39] The predictions presented in this thesis are not intended to be used as planning assumptions for militaries, national security strategy, or force development. Rather, predications are provided to test and revise the underlying analysis. The title of this thesis is based on the

[39] Danzig, "Driving in the Dark."

traditional Greek conception where, "the past and the present are in front of us—we can see them. The future, invisible, is behind us."[40]

Imagine walking backwards through a city; you must rely upon your observations of what you already walked past to predict what comes next. What do you focus on: the ground, street signs, buildings you walk past? All may be useful indicators for various aspects of what comes next, but ultimately all are imperfect indicators. For example, focusing on the ground may indicate if you have reached the curb and are about to step into a street, while the buildings and businesses near you may indicate the sort of neighborhood you are in, for example if the next building you pass is likely to be a store or a home.

Similarly, this thesis uses observations of the past and present to imagine what comes next. The past and present provides the only available evidentiary basis, so it must be relied upon in considering the future. Therefore, it is critical the scope of analysis is inclusive of examples from the past and present, which are closely related to the future thing, to provide a foundation for predicting what comes next. Accordingly, an inclusive definition of autonomous weapons is used to identify what is likely to stay the same and what is changing. Specific predictions are provided not as high confidence statements of future events, but to establish a basis for subsequent revisions to the underlying analysis as time progresses and additional information is available—in this method predictions are valuable even as they are falsified.

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[40] Bernard Knox, *Backing into the Future: The Classical Tradition and Its Renewal* (New York: W. W. Norton and Company, 1994), 11.

Recognizing the inherent uncertainty in prediction, this project is time limited to predicting just over ten years, through 2030. The year 2030 was selected due to it being a year beyond the five year budget process used by the US Government and far enough in the future to allow for technology development and maturation, yet it is proximate enough to reduce uncertainty and allow for rapid revisions in understanding where we are going as we continue to walk backwards into the future.

CHAPTER 4

ANALYSIS

The weaponization of artificial intelligence is a growing concern.
— António Guterres, UN Secretary General,
"Address to the General Assembly"

To assess how militaries are likely to use autonomous weapons through 2030, this analysis proceeds in three parts. First, what are autonomous weapons and what are their key components. Second, how have militaries used weapons with varying degrees of autonomy and what does this suggest about how they are likely to be used in the future. Finally, what are the relevant technological trends effecting the effectiveness of autonomous weapons.

Ontological: What are Autonomous Weapons?

Current literature uses a range of definitions for autonomous weapons, and autonomy more generally. Autonomy is commonly described based on either the expected degree of user involvement or the complexity of the computation involved. For example, in the automotive industry a six-level model is commonly used where the key differentiating factor is the driver's involvement in the operation of the vehicle. This model defines level zero the driver performing all tasks and level five there is no human driver present.[41] Scharre, amongst others, complements the user-role model with a

[41] SAE International, J3016-201806, *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles* (Warrendale: SAE International, June 2018), accessed 18 February 2018, https://www.sae.org/standards/content/j3016_201806/.

computation complexity model to describe autonomy. He describes a spectrum from automatic to automated to autonomous where the differentiating factor is the complexity in the computation linking a sensory input to an action, where "complexity in the computation" seems to be based on how readily understandable is the decision-making of the system.[42] Scharre notes, "In practice, the line between automatic, automated, and autonomous systems is still blurry."[43]

These framings focus analysis on emergent technologies, but the vague distinctions used in them hinder analysis and extrapolation from past and current use of similar weapons and presents challenges to effective communication and potential rule-making. As Scharre notes, "Often the term 'autonomous' is used to refer to future systems that have not yet been built, but once they do exist, people describe those systems as automated."[44]

The UK Ministry of Defense doctrine specifically notes the challenge in this ambiguity stating: "Particular care should be taken with the terms 'automated' and 'autonomous', which differ considerably between countries and equipment manufacturers."[45] UK military doctrine goes on to define "automated" and "autonomous"

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[42] Scharre, *Army of None*, 30-31.

[43] Ibid., 32.

[44] Ibid.

[45] Ministry of Defense, Joint Doctrine Publication 0-30.2, *Unmanned Aircraft Systems* (United Kingdom: Ministry of Defense, August 2017), accessed 20 February 2019, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/673940/doctrine_uk_uas_jdp_0_30_2.pdf.

by focusing on how predictable the actions of the system are, with automated being predictable and autonomous unpredictable.

This is an inherently subjective distinction—what is "predictable" depends on the predictor's familiarity with the system rather than just a property of the system itself. This distinction also presents challenges for analysis and potential policy formation by seemingly limiting the definitional scope to only future systems that do not yet exist.

The US DoDD 3000.09, *Autonomy in Weapon Systems*, defines "autonomous weapon system" as:

> A weapon system that, once activated, can select and engage targets without further intervention by a human operator. This includes human-supervised autonomous weapon systems that are designed to allow human operators to override operation of the weapon system, but can select and engage targets without further human input after activation.[46]

This directive goes on to define "semi-autonomous weapons" with the key distinction being that in semi-autonomous weapons humans select targets with the weapon system "employing autonomy for other engagement-related functions."[47] The directive also defines "target selection" as "[t]he determination that an individual target or a specific group of targets is to be engaged."[48] This directive imposes constraints on development and use of both autonomous and semi-autonomous weapons by the US DoD, but it explicitly exempts from the requirements of the directive: "cyberspace systems for cyberspace operations; unarmed, unmanned platforms; unguided munitions; munitions

[46] Department of Defense, DoDD 3000.09, *Autonomy in Weapon Systems*," 13.

[47] Ibid., 14.

[48] Ibid., 15.

manually guided by the operator (e.g., laser- or wire-guided munitions); mines; or unexploded explosive ordnance."[49]

It is ambiguous to distinguish autonomous weapons based upon a human performing target selection. Distinguishing between a system that selects a target from one that recognizes a previously selected target, seems challenging at best. Moreover, by referring to human operators in the definition, it seems to assume a human in proximity, in both space and time, to weapon employment making target selection decisions, but that is not the case for a wide range of military weapon systems. For example, a crew operating indirect fire artillery generally are not involved in target selection at all. If they fire a munition at a designated location which seeks armored vehicles, it seems this meets the definition of semi-autonomous weapon system, but it is unclear who is the human operator selecting that target. To avoiding the challenge in identifying where, when, and by whom a target selection decision is made, this thesis uses a broader definition based on the weapon sensing target attributes.

Defining Autonomous Weapons

To avoid the ambiguities and challenges of exiting definitions, this thesis applies a broad definition for "autonomous weapons" as: Things designed or used to cause harm through independent actions taken in response to sensing attributes of a target. This definition avoids more subjective aspects, while building upon the common use of "weapon" and the element of independence in the common use of "autonomy." However,

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[49] Department of Defense, DoDD 3000.09, *Autonomy in Weapon Systems*," 2.

in referring to "things" this definition does exclude the use of organisms for military purposes, for example use of bacteria or military use of dogs.[50] By requiring that harm is caused based on sensory inputs related to the target, this definition excludes, for example, systems that have autonomy related to their mobility and navigation, but not the use of their harm causing component. This definition also excludes munitions with simple time, impact, inertia, or barometric fuses, which detonate based on a reading from an internal timing mechanism, contact sensor, inertial sensor, or barometer (respectively), as such devices are acting independently based on sensory inputs regarding their motion in the environment rather than identifying attributes of a target.

This definition is intentionally broad in scope, it includes things which people have long used in combat, for example traps, mines, proximity fused munitions, and sound-seeking torpedoes. While this is a departure from existing literature, which focuses primarily on emergent technologies, this broad definition allows for a greater empirical basis for analysis and provides for less ambiguous distinctions, thereby allowing identification of both what is changing and what is remaining constant about autonomous weapons.

Six-Factor Descriptive Model

In addition to an unambiguous definition of autonomous weapons, a descriptive model is needed to identify relevant attributes for military use and related technology development. The descriptive models used in the literature tend to focus on a specific

[50] Matthew Hipple, "Autonomous Weapons: Man's Best Friend," *The Strategy Bridge*, 9 December 2017, accessed 16 March 2019, https://thestrategybridge.org/the-bridge/2017/12/9/autonomous-weapons-mans-best-friend.

domain or are more general models of autonomous systems not adapted to identify key aspects relevant for military employment. Rather than using these existing models, a new six-factor descriptive model is used in this thesis to describe and compare autonomous weapons. This model is applied in the third analytical perspective to identify how technological innovation is likely to change autonomous weapon performance.

The descriptive model consists of munition, sensor, decider, power, mobility, and communication. The first three components (munition, sensor, and decider), are essential components due to the definition of autonomous weapons, they also directly correspond to the common framework of action, perception, and cognition used to describe autonomous systems more generally.[51] The second three components (power, mobility, and communication), are elements often present in weapon systems that are particularly relevant for subsequent analysis and comparison of various autonomous weapons. These six factors were selected for being generally applicable to autonomous weapons used in any of the five military domains and illustrative of key military aspects of range, endurance, and command and control channels.

Munition refers to the component of the system that is used to cause harm, the sorts of harms it is capable of causing, and related aspects. This includes, for example, both the expended ammunition, the gun that propels it, and its effects on targets. For example, the Samsung SGR-A1 is reported to use a 5.56mm caliber light machine-gun

[51] Office of Technical Intelligence, Office of the Assistant Secretary of Defense for Research and Engineering, *Technical Assessment: Autonomy* (Washington, DC: Government Printing Office, 2015), 2.

firing at up to 1,000 rounds per minute with an effective range of 0-3.2km;[52] such a munition is certainly lethal to personnel in the open but has little ability to penetrate armored vehicles. While discussions in the UN CCW focus on "Lethal Autonomous Weapon Systems,"[53] the ontology used in this thesis broadly considers the potential harms, both lethal or non-lethal, an autonomous weapon can cause. Considering the potential harms within the munition component, rather than applying "lethal" as a definitional threshold, allows for broader consideration of autonomous weapons—though to be considered a weapon it must be used to cause some sort of harm. Accordingly, the ontology used in this thesis is analogous to the "functional approach," advocated by the International Committee of the Red Cross, which focuses on "autonomy in the critical functions of selecting and attacking targets."[54]

Sensor refers to the elements of the autonomous weapon that are used to collect information from the surrounding environment. For example, mines and traps are commonly pressure release or pressure activated, typically either through use of a pressure plate or a tripwire. These pressure sensing devices are the sensor component of these weapons. The calibration of these mechanisms is often used to differentiate targets, for example an anti-tank mine typically requires greater pressure to activate than an anti-

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[52] Jean Kumagai, "A Robotic Sentry For Korea's Demilitarized Zone," IEEE Spectrum, 1 March 2007, accessed 20 February 2019, https://spectrum.ieee.org/robotics /military-robots/a-robotic-sentry-for-koreas-demilitarized-zone.

[53] United Nations Office at Geneva, "Background on Lethal Autonomous Weapons Systems in the CCW."

[54] International Committee of the Red Cross, "Towards Limits on Autonomy in Weapon Systems," 9 April 2018, accessed 21 February 2019, https://www.icrc.org/en /document/towards-limits-autonomous-weapons.

personnel mine. However, for the purposes of this descriptive framework calibration is considered as an element of the decider.

Decider refers to how the system computationally combines inputs of its various sensors to determine to cause harm. A decider could be a simplistic response to crossing a calibrated threshold, as in the example of mines—which other frameworks typically describe as "automatic." Alternatively, a decider may combine multiple inputs in a simple deterministic manner, perhaps using non-Turing-complete computation, to decide on use of munitions—what other frameworks likely describe as "automated." More complex systems may use a state-machine, a deterministic algorithm on a Turing-complete computer, or employ algorithms developed through modern machine learning techniques, like deep neural networks, which may make aspects of their computation undeterminable or otherwise uncertain. The decider component may use computation on-board the weapon, or, if the autonomous weapon has a communications component, may use remote computational resources—implying potentially significant trade-offs in computing performance, size, weight, power requirements, thermal characteristics, and information security. The complexity in the decider system tends to be the focus in the "spectrum of autonomy" approaches for providing a definitional threshold of what is autonomous. In contrast, this element as a component of the descriptive framework used here, to allow for greater analysis of this critical aspect.

Turning from the three essential components of autonomous weapons, the three other aspects considered are: power, mobility, and communications. Power refers to what energy is required to operate the autonomous system and how that energy is provided. Some autonomous weapons, such as traps and mines, rely upon potential energy and use passive sensors that do not require energy to operate. Other autonomous weapons may use active sensors, computation, or have other components that require ongoing energy consumption. Such energy may be provided through, for example, electricity stored in batteries or it may be generated on board through combustion, nuclear power, solar energy, or other sources. Energy for an autonomous system also could be provided by a broader system for power generation and distribution, such as a national, or local, electrical distribution system. While power is not an essential component to an autonomous weapon, it is included in the descriptive framework because how a weapon is powered significantly effects operational capabilities and constraints.

Mobility refers to how the autonomous weapon moves within the domain(s) it operates in. Mobility may be provided internal to the autonomous weapon (for example in an autonomous aircraft) or mobility may be provided externally to the weapon (for example in the case of the SGR-A1, which is transported and installed at fixed locations).[55] Mobility when applied to autonomous weapons in cyberspace refers to how they propagate across computer networks or across applications and systems running on a computer. Mobility is a particularly significant aspect due to the inherent implications for the military capability and control of autonomous weapons.

The communication capabilities of an autonomous weapon present significant implications for the potential supervisory relationship, computational, and sensor capabilities. Autonomous weapons may, for example, have no communication systems, periodic status and diagnostic, provide continuous remote status monitoring, or support

[55] Kumagai, "A Robotic Sentry for Korea's Demilitarized Zone."

remote operation of the weapon. The communication system may operate over a range of communication mediums and protocols. Expected availability and security of communications may be a particularly significant aspect that motivate the choices of militaries between manned, remotely operated, or autonomous weapons. As noted by the UN Institute for Disarmament Research, "some States consider that increasing autonomy is needed in order to operate in so-called 'degraded' environments."[56]

Distinguishing Autonomous Weapons

The final ontological aspect of autonomous weapons to consider is how to distinguish autonomy in circumstances where a weapon may operate with varying levels of independence over time or across functions. A weapon could be designed to operate autonomously on a situational basis, for example, in the event the user losses consciousness (for example a pilot performing high-G maneuvers) or, for remotely-operated systems, in the event the control channel is disrupted. Additionally, weapon systems may have autonomy in certain functions, while not being autonomous weapons. For example, most remotely operated aircraft have an autonomous "return home" function should they lose their communications link.[57] However, since autonomous return home functions are not exercising independence in their harm causing function,

[56] United Nations Institute for Disarmament Research, "The Weaponization of Increasingly Autonomous Technologies: Concerns, Characteristics, and Definitional Approaches" (Research, UNIDIR, Geneva Switzerland, 2017), accessed 16 March 2019, http://www.unidir.org/files/publications/pdfs/the-weaponization-of-increasingly-autonomous-technologies-concerns-characteristics-and-definitional-approaches-en-689.pdf.

[57] Hambling, *Swarm Troops*, 266.

such systems are excluded from the scope of the definition for "autonomous weapon" used in this thesis. In general, if the weapon causes harm through autonomous action, even if that autonomous action is an exceptional operational state (e.g. only when the control channel is jammed) or if the autonomous action is supervised by a user ("Human on the loop"),[58] then that weapon is considered an autonomous weapon.

Perhaps the most difficult edge cases on what constitutes an autonomous weapon are those weapons that use target identification and guidance systems. Consider, for example, sound-seeking torpedoes, which were used in World War II,[59] and more modern loitering munitions which air forces commonly use to target radar systems.[60] From one perspective, their autonomy could be described as just related to the mobility function; that is, it autonomously guides the munition to the target, with the user deciding to launch the system based upon identifying a target. However, given that their sensors are identifying properties of the target, and based on this sensory input independently directing the munition towards what it identifies, these are discussed as autonomous weapons in this work. In contrast, a munition that autonomously guides itself to a laser designator, or some other marker, is not considered an autonomous weapon. The key

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[58] Scharre, *Army of None*, 45.

[59] John Creighton Campbell, *Naval Weapons of World War Two* (Annapolis, MD: Naval Institute Press, 2002).

[60] James W. Canan, "Unmanned Aerial Vehicles," *Air Force Magazine* (October 1988): 84-92, accessed 21 February 2019, http://www.airforcemag.com/Magazine Archive/Documents/1988/October%201988/1088uav.pdf.

distinguishing feature of an autonomous weapon is if harm is caused as a result of an independent decision based on sensing target attribute(s).

Capability: Past, Present, and Future Uses of Autonomy

A range of factors may influence military capability development, including private business interests.[61] However, the competitive nature of the international system[62] results in incentives to states to prioritize improving military effectiveness, above other considerations, in their development and adoption of new military capabilities and technologies. Considering this competitive pressure on states to prioritize military effectiveness over other concerns, this section seeks to identify the capabilities militaries seek though autonomous weapons based on analysis of past, present, and identified planned future use of autonomous weapons. This section also demonstrates and tests the ontology presented by considering weapons near the definitional threshold of "autonomous weapons". Each of the five domains recognized in US military doctrine[63] is considered separately in order of military activity occurring in that domain.

Focusing on military effectiveness as the principle driver of military capability development logically leads to a simple top-level conclusion: Militaries are likely to use autonomous weapons if they out-perform, on a cost and risk adjusted basis, non-

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[61] Dwight D. Eisenhower, "Military Industrial Complex Speech" (Washington DC, 17 January 1961), accessed 23 February 2019, http://avalon.law.yale.edu /20th_century/eisenhower001.asp.

[62] John J. Mearsheimer, *The Tragedy of Great Power Politics* (New York: W. W. Norton and Company, 2014).

[63] Joint Chiefs of Staff, Joint Publication 3-0.

autonomous alternatives. This simple logical conclusion is enriched by the following analysis to better understand the performance, cost, and risk benefits of autonomous weapons, and the key factors drive these benefits, relative to non-autonomous alternatives. This analysis identifies four challenges autonomous weapons address which make them particularly attractive for militaries:

1. The Mundane: Persistence in observing and reacting to events over an extended period.
2. The Fast: Acting at speeds that exceed performance constraints of potential user-control systems—both in regard to reaction time (<200 ms)[64] and to human tolerances for acceleration.[65]
3. The Denied: Operating in conditions that present substantial risk to manned systems or to the security of communications channels used to remotely operated systems.
4. Mass: Increasing the military capabilities of a state relative to available population for military service.

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[64] Robert J. Kosinski, "A Literature Review on Reaction Time," Clemson University, September 2013, accessed 23 February 2019, http://www.cognaction.org /cogs105/readings/clemson.rt.pdf.

[65] Ulf I. Balldin, "Acceleration Effects on Fighter Pilots," in *Medical Conditions of Harsh Environments*, ed. Dave E. Lounsbury (Washington, DC: Office of The Surgeon General, Department of the Army, 2002), 1114-1027, accessed 23 February 2019, https://ke.army.mil/bordeninstitute/published_volumes/harshEnv2/HE2ch33.pdf.

Land

The land domain provides the earliest examples of autonomous weapon use, it is also the domain where technology advances in robotics, computation, and sensors have perhaps the greatest potential to increase the capabilities of autonomous weapons. Traps, mines, and other "victim-operated" systems are some of the earliest examples of autonomous weapons and given the challenge of movement due to terrain continue to be the most prevalent. Other notable examples of autonomy in the land domain are closely integrated into munitions, active defense systems, and emergent robotic systems; each of these are analyzed in this section. Militaries have used organisms (including dogs, other animals, and bacteria) as autonomous weapons, but these are not analyzed here to keep the scope of this work focused on tools people develop rather than organisms coopted or trained to cause harm.

People have long used victim-operated weapons, and such weapons are continuing to increase in sophistication. Traps appear to have been used for hunting since at least the Neolithic period,[66] and victim-operated traps with an explosive munition have been used in combat since at least the 14th Century.[67] In the 19th Century, the lethality and reliability of mines significantly increased with the invention of dynamite, resulting in military use of land mines rapidly increasing and mines being equipped with a diverse

[66] Andrew Huggert, "A Self-triggered Device to Catch Elk as Early as the Neolithic: A Study from an Archaeological and Ethnological Point of View," *Acta Borealia* 19, no. 2 (2002): 181.

[67] Joseph Needham, *Science and Civilisation in China: Volume 5, Chemistry and Chemical Technology, Part 7, Military Technology: The Gunpowder Epic* (New York: Cambridge University Press, 1987), 199.

range of fuses and triggers.[68] In 2007, Iraq insurgents used explosively formed projectiles triggered by passive infrared sensors to target US forces.[69] Interestingly, the increase in passive infrared-activated explosively formed projectiles seem to have corresponded to the fielding of electronic counter-measures to defeat radio-controlled explosive devices—suggesting greater autonomy being adopted due to a control channel becoming denied. Modern mines may combine multiple sensors to increase their effectiveness, for example the Soviet TM-83 mine combines a seismic sensor and an infrared sensor to target military vehicles.[70] Future systems could combine additional sensors and computational capacity to further discriminate targets, potentially differentiating between friendly and enemy vehicles, they could also potentially designed for mobility or to launch various munitions to extend their range and effectiveness.

Over the past century, militaries have closely integrated sensors into ammunition to improve their effectiveness. During World War II, the United Kingdom and United States collaborated to develop proximity fuses (also known as VT or Variable Time fuses), which greatly increased the effectiveness of artillery, particularly anti-aircraft

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[68] William C. Schneck, "The Origins of Military Mines: Part I," *Engineer Bulletin*, July 1998, accessed 1 April 2019, https://fas.org/man/dod-101/sys/land/docs/980700-schneck.htm.

[69] Clay Wilson, *Improvised Explosive Devices (IEDs) in Iraq and Afghanistan: Effects and Countermeasures* (Washington, DC: Congressional Research Service, 2007), 3, accessed 1 April 2019, https://fas.org/sgp/crs/weapons/RS22330.pdf.

[70] Collaborative Ordnance Data Repository, "U.S.S.R. LANDMINE, AT, TM-83," Center for International Stabilization and Recovery, accessed 1 April 2019, https://ordata.info/ordnance?id=3959.

artillery.[71] Early proximity fuses used short range radar to detect when a shell was within a set distance from the ground or an aircraft.[72] In 2015, US Defense Advanced Research Projects Agency (DARPA) demonstrated the EXACTO guided bullet—a .50 caliber round fired from a standard rifle but remotely guided while inflight to hit a target.[73] While the DARPA EXACTO guided bullet was remotely guided, rather than autonomous, it suggests the future possibility to integrate advanced sensors, communication, and computation on to small ammunition to enable rounds to autonomously identify and seek targets, potentially greatly increasing the range, accuracy, and lethality of even small arms.

The third set of land-based autonomous weapons are active defense systems. Early in World War II, the United States and United Kingdom collaborated to develop the SCR-548 radar system (sensor), which was subsequently integrated with an M-9 gun director (decider), and four 90mm guns firing shells with proximity fuse (munition).[74] The system was manned, in that it required personnel to load the guns and operate the

[71] Ralph B. Baldwin, *The Deadly Fuze: The Secret Weapon of World War I* (San Rafael, CA: Presidio Press, 1980), 4.

[72] John W. Kyle, Radio Proximity Fuze, U.S. Patent 3,152,547, filed 4 December 1950, issued 13 October 1964, accessed 1 April 2019, https://pdfpiw.uspto.gov /.piw?docid=03152547.

[73] Defense Advanced Research Projects Agency, "EXACTO Guided Bullet Demonstrates Repeatable Performance against Moving Targets," 27 April 2015, accessed 1 April 2019, https://www.darpa.mil/news-events/2015-04-27.

[74] David A. Mindell, "Automation's Finest Hour: Bell Labs and Automatic Control in World War II," *IEEE Control Systems Magazine* (December 1995): 72-80, accessed 30 March 2019, http://www.ieeecss.org/CSM/library/1995/dec1995/05-BellLabsnAutoCtrl.pdf.

large and complex system; however, its critical functions were fully automated with the M-9 gun director directly taking inputs from the SCR-548 radar to calculate the aim point for the guns, aim the guns through servos, and determine the settings necessary for either timed or proximity fuses. This anti-aircraft system proved highly effective in World War II, but its greatest application was in shooting down V-1 rockets, as General Frederick A. Pile, the British head of the Anti-Aircraft command, said "It seemed to us that the obvious answer to the robot target or the flying bomb [the V-1] . . . was a robot defense."[75]

The basic components of the SCR-548 radar-based anti-aircraft system continues to be used in advanced protection systems today. The Israel designed, and the United States adopted, Trophy active protection system, equips vehicles with a radar system to detect incoming projectiles, and computes and launches countermeasures to defeat the incoming projectile.[76] Similarly most air defense systems, like the US Patriot or Swiss Skyguard GDF-005, operate functionally the same based on autonomous radar detection and rapid computation of a firing solution to engage. Such systems are likely to continue to increase in performance as they integrate additional sensors and computational power to detect and engage threats faster and further out; there is also potential to use directed-energy weapons to engage some threats in a repeatable manner. Defeating active protection systems, may involve ammunition with multiple projectiles or autonomous navigation to allow for random variation in trajectory to avoid interception.

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75 Mindell, "Automation's Finest Hour," 78.

76 IAI Elta, "WindGuard Radar, ELM-2133" (Product Brochure, May 2010), accessed 1 April 2019, http://www.iai.co.il/sip_storage/FILES/8/38048.pdf.

Autonomous weaponized robots, while the subject of substantial science fiction and popular interest, have yet to be observed in military use. The closest to such systems are stationary sentry weapons like the Israel Sentry Tech or the South Korean SGR-A1 and Super aEgis II.[77] Such systems use multiple sensors to detect and identify targets and are described by their manufacturers as capable of autonomously engaging targets, despite their customer militaries generally remotely operating them. Remotely operated land-based robots used by militaries have typically been unarmed, like the Packbot, and used to remotely explore buildings or for bomb disposal. However, in July 2016, Dallas police department equipped a such a robot with explosives to kill Micah Johnson, who had shot five police officers and was in defensive position in a parking garage.[78] On 6 February 2019, the Russian Advanced Research Foundation, posted a video demonstrating a remotely operated gun system mounted on a small tracked vehicle.[79] On 29 March 2019, the US Army posted a request for proposals for an "Optionally Manned Fighting Vehicle," this request for proposals required "detailed designs for each autonomous control of the steering, braking, accelerating, turret control, gear

[77] Boulanin and Verbruggen, "Mapping the development of Autonomy in Weapon Systems," 127.

[78] Chris Kenning, "No Charges for Dallas Officers who Killed Sniper with Robot Bomb," *Reuters*, 31 January 2018, accessed 1 April 2019, https://www.reuters.com /article/us-texas-crime/no-charges-for-dallas-officers-who-killed-sniper-with-robot-bomb-idUSKBN1FK35W.

[79] Фонд перспективных исследований, "Экспериментальная платформа 'Маркер,'" *YouTube*, 6 February 2019, accessed 1 April 2019, https://www.youtube.com /watch?v=HfYuDHphx1M.

actuators/selectors, and associated cabling installed on the NGCV-OMFV."[80] Such systems, even if initially primarily remotely operated, have the potential to shift to increasingly autonomous operation on the future based purely on software changes.

Considering the range and history of land-based autonomous and unmanned weapons, it seems likely improved and increasingly autonomous functions will be pursued by militaries through 2030. The autonomous mobility of such systems is likely to be constrained due to the cluttered and complex nature of the land domain; however, improvements in sensors and decider capabilities could change this overtime. Even with constrained mobility, autonomy is likely to be an increasing factor, even as humans remain involved for some functions. Systems like Trophy, which already detect the launch location of incoming projectiles, could easily be adapted to autonomously return fire. Similarly, sentry guns could potentially be programmed to identify enemy weapon systems and automatically return fire, and be mounted on vehicles, allowing for their use to support friendly offensive or defensive maneuvers while minimizing the risk of fratricide. Similarly, existing mines could integrate additional sensors to become more lethal and discriminatory, and further improved by carrying multiple munitions to allow them to engage multiple targets simultaneously from a stand-off range. Finally, a wide range of ammunition can potentially radically be improved by integrating sensors, like the EXACTO demonstration, to greatly improve their range and accuracy—and such

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[80] Army Contracting Command, "Optionally-Manned Fighting Vehicle (OMFV) Program," Solicitation Number: W56HZV-18-R-0174, Federal Business Opportunities, 29 March 2019, accessed 1 April 2019, https://www.fbo.gov/index?s=opportunity &mode=form&tab=core&id=baed7a7339a58f4b77d5649933ba6c3e&_cview=0.

changes may be essential as a countermeasure to overcome active protection systems like Trophy and Arena.

Maritime

Use of autonomous weapons in the maritime domain originates with the related development of mines and torpedoes in the 19th century. While early mines were stationary and remotely detonated, like those used by Russia in the Crimean War of (1853 to 1856), contact fuse soon came into use, and then in 1866 Robert Whitehead designed the first self-propelled torpedo.[81] Over the next 40 years technology developments in this area focused on improving the reliability of the contact fuses, explosive yields, and for torpedoes improving their speed, accuracy, and range of delivery methods (for example dropping from airplanes). While there were international efforts to ban such weapons, the 1905 Hague Conventions only imposed modest constraints on mine use. Both mines and torpedoes played a substantial role in World War I.[82] Since the devices used in this period never developed a more sophisticated detonation method than contact fuses, they do not meet the threshold to be considered autonomous weapons.

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[81] E. W. Jolie, *A Brief History of U.S. Navy Torpedo Development* (Newport, RI: Naval Underwater Systems Center, September 1978), 7, accessed 29 March 2019, http://large.stanford.edu/courses/2015/ph241/hernandez2/docs/TorpDevel-Usn-JolieNusc1978.pdf.

[82] Norman Youngblood, *The Development of Mine Warfare: A Most Murderous and Barbarous Conduct* (Westport, CT: Greenwood Publishing Group, 2006).

It was the development and integration of acoustic and magnetic detectors and detonators that pushed mines across the autonomous threshold. Late in World War I, Britain developed acoustic and magnetic detonators for mines, ultimately fielding the Mk IM; concurrently Germany developed magnetic detonators for torpedoes.[83] During World War II, these advances were further built upon with Germany and the United States both developing passive acoustic homing torpedoes, which would guide the torpedo towards the noise generated by a ships propellers.[84] Passive acoustic homing torpedoes were less effective on ships moving slowly or employing noise-making countermeasures, so the United States began developing an active acoustic homing torpedo to improve performance, which ultimately was fielded in 1951 as the Mk 32 Mod 2.[85] Modern naval mines and torpedoes combine multiple sensors to better identify, distinguish, and engage target while overcoming countermeasures, for example the Russian Navy is reported to have fielded the Futlyar torpedo, which combines acoustic and thermal seeking.[86]

In comparison to mines and torpedoes, militaries have been slow to use remotely operated or autonomous maritime vehicles. In 1898, Nikola Tesla patented remotely controlling a vehicle by use of radio signals, publicly demonstrating this technology

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[83] Norman Friedman, *Naval Weapons of World War One* (London: Seaforth Publishing, 2011), 339.

[84] Jolie, *A Brief History of U.S. Navy Torpedo Development*, 31.

[85] Ibid., 39.

[86] TASS, "Russian Navy to Receive Advanced Futlyar Torpedoes," TASS, Russian News Agency, 22 June 2016, accessed 29 March 2019, http://tass.com /defense/883900.

using a small boat. In his patent he identifies a wide range of potential applications but sees its greatest value in increasing the certainty and destructiveness of warfare and thereby bring about peace.[87] Despite this bold claim and early work, unmanned surface and undersea vehicles largely went unpursued by militaries through the end of World War II. One of the first autonomous underwater vehicles was the unmanned Self-Propelled Underwater Research Vehicle, which was developed in 1957 by the University of Washington Applied Physics Laboratory for the US Office of Naval Research and used for oceanography purposes through 1979.[88] Today, the US Navy fields multiple unmanned service and subsurface vehicles, which primarily focus on countering mines, and intelligence functions, with future plans for armed systems.[89]

The final set of maritime systems to be considered are close-in weapon systems which are used on ships to engage incoming threats. In 1976, the Soviet Union fielded one of the first close-in weapon systems, the AK-630, followed shortly by the United States fielding the Phalanx system in 1980. These two systems, with subsequent upgrades, continue to be the most widely used systems, with 22 countries using the

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[87] Nikola Tesla, "Method of and Apparatus for Controlling Mechanism of Moving Vessels or Vehicles," US Patent No. 613,809, 8 November 1898, accessed 29 March 2019, https://pdfpiw.uspto.gov/.piw?docid=00613809.

[88] Robert W. Button, John Kamp, Thomas B. Curtin, and James Dryden, *A Survey of Missions for Unmanned Undersea Vehicles* (Santa Monica, CA: RAND Corporation, 2009), 1, accessed 29 March 2019, https://www.rand.org/content/dam/rand/pubs /monographs/2009/RAND_MG808.pdf.

[89] Jon Rucker, CAPT, "Status of Unmanned Systems: EXECUTING!" U.S. Navy, January 2018, accessed 29 March 2019, https://www.navsea.navy.mil/Portals/103 /Documents/Exhibits/SNA2018/UnmannedSystems-Rucker.pdf?ver=2018-01-11-145102-270.

Phalanx and 19 using the AK-630.[90] Both systems primarily use radar to identify targets, and internal resources to compute an engagement plan and fire their 20mm, for the Phalanax, or 30mm, for the AK-630, machine gun to engage the incoming threat.[91] There are at least twelve other similar systems in operation world-wide.[92] The United States is currently developing laser systems to improve the performance, range, and engagement-cost relative to existing ballistic systems.[93]

The development of autonomy in the maritime domain suggests two potential aspects of future military use of autonomous weapons. First, is autonomy being closely integrated into munitions, as in the case of torpedoes and mines, rather than on large combat platforms. Instead of imagining ships becoming autonomous, instead imagine a technology development path where munitions of today become increasingly autonomous, with longer loitering times, and containing increasing number of munitions. Second, autonomous weapons in the maritime domain likely not require advanced sensors or computation. The long history of use of existing systems suggests adequate performance can be achieved with simple computational and sensor components. Future improvements in computation and sensors are not critical requirements for adoption,

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[90] Boulanin and Verbruggen, "Mapping the Development of Autonomy in Weapons Systems." 125.

[91] Ibid., 36.

[92] Ibid., 125.

[93] Robert Bruce, "The US Navy's Electric Weaponry," *Small Arms Defense Journal*, 16 February 2016, accessed 29 March 2019, http://www.sadefensejournal.com /wp/?p=3459.

instead they are likely to enable faster reaction and engagement, longer ranges, greater accuracy, and reduced risk of incorrect engagements.

Air

Unmanned[94] (though more specifically remotely piloted) aircraft have become, since the start of the global war on terrorism, the subject of substantial popular attention and a focus of capability development for militaries. Unmanned aircraft have also been a key focus of advocacy groups concerned about autonomous weapons—with one such video receiving nearly 3,000,000 views on *YouTube* as of 18 March 2019.[95] However, military use of unmanned aircraft as weapons predates the first flight of the Wright brothers and unmanned aircraft have been used throughout the 20th century. Given the challenges and limitations of manned aircraft, there is substantial potential for increased use of autonomous weapons in aerial combat.

The history of unmanned aircraft is longer than commonly recognized. In 1849, Austrian military used unmanned balloons equipped with bombs to attack Venice, due to being unable to safely engage the city with available artillery.[96] Nearly 100 years later, in 1944 and 1945, Japan launched more than 9,000 balloon-borne bombs to attack North

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[94] "Unmanned" is used to refer to remotely operated, autonomous systems, and other things without a person present.

[95] Stop Autonomous Robots, "Slaughterbots," *YouTube*, 12 November 2017, accessed 18 March 2019, https://www.youtube.com/watch?v=9CO6M2HsoIA.

[96] Russell Naughton, "Remote Piloted Aerial Vehicles: An Anthology" (Essay, Monash University, 2005), accessed 18 March 2019, http://www.ctie.monash.edu.au /hargrave/rpav_home.html.

America in the last year of World War II.[97] In both cases, the balloons depended on winds to carry them above their targets, prevailing sea-to-shore winds in the Austria case and the North Pacific Jetstream in the Japan case. In the Austria case the balloon-bombs had a time of flight of about 30 minutes, and bombs were detonated by either a cooper command wire that ran back to the launch site or by a timer mechanism on the balloon, therefore the Austrian balloon-bombs neither involved a sensor or decider component and were clearly not autonomous weapons.

The Japanese balloon-bomb presents a more interesting case. These balloons used a mercury barometer to sense the altitude and trigger the release of ballast (two sand bags) when the balloon dipped to about 30,000 ft, thereby allowing the balloon to raise back to 38,000 ft. This was repeated 17 times, after which an explosive charge was detonated to release the bomb and destroy the balloon, constituting a simple pre-calibrated mechanical decider component. The role of the barometer presents an interesting question of if the Japanese balloon-bombs constitutes an autonomous weapon.

The release of the munition can most reasonably be described as effectively being based on a timer not a sensory input pertaining to the target. That is, time was indirectly measured through oscillation in the balloon's cruising altitude, and this time was pre-calculated to correspond to when the bomb was over North America. One could potentially consider the release of the bomb as being based on the sensory-input of the barometer, and argue that the balloon-bomb and, therefore, all munitions with barometric

[97] Robert C. Mikesh, *Japan's World War II Balloon Bomb Attacks on North America* (Washington, DC: Smithsonian Institution Press, 1973), accessed 18 March 2019, https://repository.si.edu/bitstream/handle/10088/18679/SAoF-0009-Lo_res.pdf.

fuses are autonomous weapons. However, such an approach would suggest munitions with impact or inertial fuses and penetrating munitions (which typically use a combination of impact and time fuses) also constitute autonomous weapons. Rather, it is more reasonable to recognize the Japanese balloon-bombs as not independently causing harm based on sensing attributes of a target, and therefore not constituting an autonomous weapon.

Military use of heavier-than-air-flight has also long involved weapons that are suggestive of autonomy. During World War I, both the United Kingdom and the United States developed unmanned fixed wing aircraft armed with explosives.[98] Elmer Sperry was amongst the early inventors of such systems, filling for a patent in 1917 for an unmanned airplane, equipped with a bomb, that could be remotely piloted by radio signals, or configured to fly a predetermined route and distance before arming and then releasing the bomb.[99] The Sperry aircraft, and others, were notable for their early integration of gyroscopic stabilization, barometric-altitude control, and remote radio control. However, these early unmanned aircraft did not include any sensors that could detect target attributes, and as such did not constitute autonomous weapons.

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[98] Hambling, *Swarm Troopers*, 11.

[99] Elmer A. Sperry, "Wireless Controlled Aerial Torpedo," U.S. Patent 1,792,937, filed 18 December 1917, issued 17 February 1931, accessed 23 March 2019, https://patents.google.com/patent/US1792937A/.

Figure 1. The Kettering Bug, developed in 1917 by Charles F. Kettering for the US Army Air Service

Source: National Museum of the US Air Force, "Kettering Aerial Torpedo "Bug," accessed 22 April 2019, https://www.nationalmuseum.af.mil/Visit/Museum-Exhibits/Fact-Sheets/Display/Article/198095/kettering-aerial-torpedo-bug/.

Following the invention of the television, the capabilities of remotely operate aircraft greatly increased. In World War II, the US Navy developed the TDR-1, which was a fixed wing airplane that was equipped with a television camera and could carry up to a 1,000 lb bomb. A pilot viewed a monochromatic 40 Hz television feed and controlled the TDR-1 through radio signals from approximately seven miles away.[100] The United

[100] Naval Drones, "TDR-1 Edna," accessed 24 March 2019, http://www.navaldrones.com/TDR-1.html.

States military used similar airplanes, remotely operated based on a broadcast television signal from the aircraft in Korea and Vietnam.[101] While these systems automated various aspects of their navigation and mobility, they certainly were not autonomous weapons, given that a remotely located operator remained in control. However, they were often used for the most hazardous reconnaissance, decoy, and attack missions against enemy anti-aircraft defenses, and, in Vietnam demonstrated ability to outperform manned fighter aircraft by executing high-speed turns.[102]

Today, both manned and remotely operated aircraft commonly integrate autonomy in various functions. For example, in maintaining a flight pattern, take-off and landing, and sensor operation for target detection and identification. Current developments efforts, including by the United States and United Kingdom, are focusing on unmanned aircraft swarms, where a fleet of unmanned aircraft operates in conjunction with a manned aircraft or are controlled remotely.[103] Unmanned high-speed stealth aircraft like the UK's Taranis[104] and US XQ-58A Valkyrie[105] demonstrate the potential

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[101] Hambling, *Swarm Troopers*, 15-24.

[102] Ibid., 21.

[103] Joseph Trevithick and Tyler Rogoway, "Let's Talk about the U.K.'s Sudden Move to Field a Drone Swarm Squadron," The Warzone, 12 February 2019, accessed 1 April 2019, https://www.thedrive.com/the-war-zone/26467/u-k-s-sudden-move-to-field-a-drone-swarm-squadron-may-point-to-bigger-unmanned-developments.

[104] BAE Systems, "Taranis," accessed 1 April 2019, https://www.baesystems.com /en/product/taranis.

[105] 88 Air Base Wing Public Affairs, "XQ-58A Valkyrie Demonstrator Completes Inaugural Flight," US Air Force, 6 March 2019, accessed 1 April 2019, https://www.wpafb.af.mil/News/Article-Display/Article/1777743/xq-58a-valkyrie-demonstrator-completes-inaugural-flight/.

unmanned systems to compete effectively against modern militaries and augment more expensive manned aircraft. Remotely piloted aircraft typically have a return home feature, to autonomously navigate to a designated location, in the event communications are lost. However, in combat it may be preferable when communications are lost to have such systems autonomously complete their mission or target emitters that may be jamming their communications. Existing remotely piloted aircraft likely could be readily converted with relative simply configuration, software, and computing hardware changes.

In addition to aircraft, autonomy is commonly used in precision guided munitions, loitering weapons, and air defense systems. Modern precision guided munitions use multiple sensors to detect and guide the munition towards targets. For example, the Raytheon StormBreaker is described as using millimeter wave radar, uncooled imaging infrared, semi-active laser, global positioning system, and inertial guidance, to track target and guide the bomb to the target.[106] Such weapons are also increasingly equipped with home-on-jam systems, which identify radio jamming and guide the munition to the source of that signal.[107] Such munitions contain all the components of an autonomous weapon—in addition to having two-way data links such munitions typically have batteries on board that power computation to process and act on signal inputs. While

[106] Raytheon, "StormBreaker Smart Weapons," accessed 24 March 2019, https://www.raytheon.com/capabilities/products/stormbreaker.

[107] Joe Gould, "Guided-Bomb Makers Anticipate GPS Jammers," *Defense News*, 31 May 2015, accessed 14 March 2019, https://www.defensenews.com/air/2015/05/31/guided-bomb-makers-anticipate-gps-jammers/.

many such systems glide to their target, the Select Precision Effects at Range Capability 3 being developed for the UK Ministry of Defence uses powered flight.[108]

Loitering weapons, unlike precision guided munitions, are designed to patrol a designated area for an extended period searching for and then engaging targets. The Israel Harpy Next Generation (Harpy NG), produced by International Association for Identification, is a particularly notable system. The Harpy NG is describing as having a loitering time of nine hours and can be remotely operated or operated fully autonomously.[109] The Harpy NG is an autonomous anti-radiation seeker—that is it identifies and guides itself to radio frequency transmitters within a designated target area.[110] The persistence such weapon systems provide in patrolling hostile airspace make for substantial military utility and are likely to be increasingly used by militaries.

Modern air defense systems also employ autonomous weapons to rapidly identify and engage aircraft, rockets, and missiles. Air defense systems are used by at least 89 countries.[111] Such systems typically use radar and radio signals from Identification, Friend or Foe to detect and classify incoming threats and alert human users to make an

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[108] MBDA Systems, "MBDA Showcases the SPEAR Precision Strike Missile for the F-35," 12 July 2016, accessed 24 March 2019, https://www.mbda-systems.com/press-releases/mbda-showcases-the-spear-precision-strike-missile-for-the-f-35/.

[109] Boulanin and Verbruggen, "Mapping the Development of Autonomy in Weapons Systems," 54.

[110] Israel Aerospace Industries, "Harpy NG," accessed 20 March 2019, http://www.iai.co.il/2013/36694-16153-en/IAI.aspx.

[111] Boulanin and Verbruggen, "Mapping the Development of Autonomy in Weapons Systems," 37.

engagement decision, or to override a planned engagement. Incidents like the 1988 shooting down of Iranian Air Flight 655 by the Aegis Combat System[112] and the two fratricide incidents in Operation Iraqi Freedom[113] provide cautionary examples of how the challenge of human-automation integration can contribute to engagement errors.

Future autonomous weapon use in the air domain is likely to focus on defeating integrated air defense systems, increasing persistence, and increasing the range and performance of both air defense systems and manned aircraft. The Israeli Harpy and Harpy NG have demonstrated the utility of autonomy in defeating air defense systems and the importance of autonomy in this role seems to be increasing as states field additional electronic warfare capabilities. Autonomous aircraft have the potential to provide continuous air patrols, overtime gaining the ability to engage an increasing variety of targets from the easily distinguished to the more ambiguous. Autonomous aircraft also have substantial potential in an air supremacy role, as they overcome the human constraints in high acceleration, allowing them to potentially outmaneuver and engage other aircraft far faster than manned fighters. Finally, advances in autonomous systems have the potential to identify aerial threats at increasing ranges and extend

[112] William M. Fogarty, "Formal Investigation into the Circumstances Surrounding the Downing of Iran Air Flight 655 on July 3, 1989," Department of Defense, 19 August 1988, accessed 20 March 2019, https://apps.dtic.mil/dtic/tr/fulltext/u2/a203577.pdf.

[113] John Hawley, *Patriot Wars: Automation and the Patriot Air and Missile Defense System* (Washington, DC: Center for a New American Security, 2017), accessed 7 May 2019, https://www.cnas.org/publications/reports/patriot-wars.

engagement distances—such capabilities can improve ground-based air defenses multiple while also augmenting the capabilities of manned aircraft.

Space

Space presents a unique case among the five domains, as the only one where there is no available evidence of weapon use in space (as distinct from anti-satellites weapons launched from Earth).[114] However, military and civilian agencies recognize autonomy as a desirable feature in a wide range of space systems due to the hazards and distances inherent in space and the resulting communications constraints. Potential military applications of autonomy in space can be inferred from the work of these civilian agencies.

The National Aeronautics and Space Administration identifies autonomy as a needed capability for overcoming communications constraints, making time-critical decisions, reduce cost, and improve performance of systems operating in space.[115] Similar, the European Space Agency has experimented with autonomy in satellites, launching the Prototype Research Instruments and Space Mission technology

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[114] Daniel R. Coats, "Worldwide Threat Assessment of the US Intelligence Community" (Statement for the Record, Office of the Director of National Intelligence, 29 January 2019), 17, accessed 10 March 2019, https://www.dni.gov/files/ODNI /documents/2019-ATA-SFR---SSCI.pdf.

[115] Terry Fong, "Autonomous Systems: NASA Capability Overview," NASA, 24 August 2018, accessed 10 March 2019, https://www.nasa.gov/sites/default/files/atoms /files/nac_tie_aug2018_tfong_tagged.pdf.

Advancement to demonstrate autonomous formation flying in low earth orbit.[116] The work of these agencies recognize a wide range of applications for autonomy from orbital station keeping, improving the performance of satellite constellations, to distant space exploration.

Autonomy may provide space-based counter-measures to anti-satellite weapons, allowing satellites to detect and rapidly adjust their course to avoid anti-satellite weapons. Such systems could also be used to target and destroy anti-satellite weapons or to target satellites. Considering the cost and hazards of manned space systems and the inherent communications delays from the surface of the Earth,[117] the hazardous nature of space provides clear utility for autonomy in military space systems in overcoming the intrinsically "Denied" nature of space as an operating domain to humans.

Cyberspace

Weapons in cyberspace are simply software[118] that is designed or used to cause harm. Unlike the physical domains, humans do not move through cyberspace and primarily interact with it through established interfaces, which presents challenges to distinguishing autonomous weapons from non-autonomous. To make this distinction, the critical factor to focus on is if harm is caused through independent action based on

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[116] Herbert Kramer, "PRISMA (Prototype Research Instruments and Space Mission Technology Advancement)," European Space Agency, accessed 10 March 2010, https://earth.esa.int/web/eoportal/satellite-missions/p/prisma-prototype.

[117] It takes approximately 120ms for a signal from the surface of the Earth to reach a satellite in geosynchronous orbit (35,786 km divided by the speed of light).

[118] Software is a set of instructions executed by a computer.

sensory inputs, rather than using the common, but misleading, litmus test of if the weapon is manned or unmanned.

First, consider software that used to cause harm, but through non-autonomous use. Remote access tools are software that provide remote access to a computer. For example, Back Orifice was an early remote access tool, that was released by Cult of the Dead Cow at Defcon VI on 1 August 1998 to demonstrate security weaknesses of Windows, but could be used by a range of individuals for malicious purposes.[119] Such tools are commonly developed, distributed, and used illicitly—for example, in 2015 Alex Yücel pled guilty to his role in developing and distributing the popular Blackshades remote access tool.[120] Such tools have been used to cause harm, but have done so by providing a remote actor access to the system to execute commands rather than through independent operation. That is, they lack both a munition and a decider and as such have no independent ability to cause harm, therefore, remote access tools are not autonomous weapons.

In contrast to remote access tools, worms are software programs that are self-propagating, and, therefore, more likely to constitute autonomous weapons. One of the first computer worms that propagated over the Internet was the Morris worm of 1988, which substantially disrupted the operation of various computers connected to the

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[119] Cult of the Dead Cow, "Back Oriface," 21 July 1998, accessed 9 March 2019, https://www.cultdeadcow.com/news/back_orifice.txt.

[120] Southern District of New York, "Co-Creator of 'Blackshades' Malware Pleads Guilty in Manhattan Federal Court," Department of Justice, 18 February 2015, accessed 9 March 2019, https://www.justice.gov/usao-sdny/pr/co-creator-blackshades-malware-pleads-guilty-manhattan-federal-court.

Internet at that time.[121] When executed the Morris worm would use common network applications to autonomously identify potentially vulnerable systems (sensing), propagating to those systems (mobility) based on defined criteria.[122] It used various obfuscation techniques to ensure it could continue to operate on infected computers (decider and power)[123] and attempted to send a UDP packet to ernie.berkley.edu after approximately every 15 infections (communication).[124] However, the Morris worm did not contain a munition, instead harms were produced as a side-effect of it using the power and processing resources of infected computers as it autonomously propagated.

Subsequent computer worms have carried a variety of payloads, from installing remote access tools to ransomware.[125] One particularly notable worm was Stuxnet, which some journalists described as the "world's first real cyberweapon."[126] Stuxnet substantially differed from other worms in its specific targeting and destructive potential. It was designed to identify specific systems operating centrifuges and then manipulate the

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[121] Eugene Spafford, "The Internet Worm Program: An Analysis" (Technical Report CSD-TR-823, Department of Computer Science, West Lafayette, IN, December 1988), accessed 9 March 2019, https://spaf.cerias.purdue.edu/tech-reps/823.pdf.

[122] Spafford, "The Internet Worm Program," 7-10.

[123] Ibid., 8, 11.

[124] Ibid., 11.

[125] VeraCode, "Computer Worm," accessed 9 March 2019, https://www.veracode.com/security/computer-worm.

[126] Kim Zetter, "How Digital Detectives Deciphered Stuxnet, the Most Menacing Malware in History," *Wired*, 11 July 2011, accessed 9 March 2019, https://www.wired.com/2011/07/how-digital-detectives-deciphered-stuxnet/.

spin rate of those centrifuges to destroy them.[127] Accordingly, Stuxnet had all three components essential to an autonomous weapon: munition, sensor, and decider. By operating as a worm using multiple propagation techniques, not dependent on an Internet connection, it was able to infect, and achieve effects, on systems where it could not communicate with whomever was using Stuxnet to target Iranian centrifuges. Its design also allowed for persistence and stealth in intermittently altering the spin rate of centrifuges potentially over a period of multiple years.[128]

Based on the example of worms, several key capabilities of autonomy in cyber weapons can be deduced. First, is the ability to infect and achieve effects on "air-gapped" systems—that is systems that are not connected to the Internet or other means for remote access. Second, is the persistence and stealth achievable by having a cyber weapon that does not require any remote communication or operation. Third, by operating autonomously cyber weapons can achieve staggering speed and scale constrained only by the speed of networks and computers, rather than humans. Given the non-physical nature of cyberspace and these capabilities, it seems likely that militaries will tend to use autonomous cyber weapons, to include for defensive purposes in countering cyber weapons, instead of depending on live remote access to conduct cyber operations.

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[127] Ralph Langner, "To Kill a Centrifuge: A Technical Analysis of What Stuxnet's Creators Tried to Achieve," The Langer Group, November 2013, accessed 9 March 2019, https://www.langner.com/wp-content/uploads/2017/03/to-kill-a-centrifuge.pdf.

[128] Geoff McDonald, Liam O. Murchu, Stephen Doherty, and Eric Chien, "Stuxnet 0.5: The Missing Link" (Symantec Report, 26 February 2013), accessed 9 March 2019, http://www.symantec.com/content/en/us/enterprise/media /security_response/whitepapers/stuxnet_0_5_the_missing_link.pdf.

Perhaps it is in recognition of this that DoDD 3000.09 specifically excludes application of the directive from "cyberspace systems for cyberspace operations."[129]

Technology Readiness and Risk

Technology presents constraints and risks to potential military capabilities. Technology does not just enable increased autonomy, but also may allow for increased human control—as demonstrated in the evolution of unmanned aircraft from autonomous to remote piloting. On the other hand, technology risks, like those from cyber operations and electronic warfare, may result in new denied environments compelling use of increased autonomy instead of remotely operated systems. Finally, the adoption of autonomous systems may lead to the completive need to adopt autonomy as an effective counter—as seen in the case of integrated air defense in countering V1 rockets.

This section considers likely near-term technological developments that are relevant to military use of autonomous weapons through 2030. The six-factor descriptive model introduced in the ontological section (munition, sensor, decider, power, mobility, and communication) is used to frame this analysis. This analysis considers risks and competitive pressures related to autonomous weapons, as well as potential constraints on autonomous weapon systems. Military technological developments are sometimes classified or proprietary, limiting availability of information to support this analysis. Like other reports on autonomous weapons,[130] this section relies heavily on US military

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[129] Department of Defense, DODD 3000.09, *Autonomy in Weapons Systems*, 2.

[130] Boulanin and Verbruggen, "Mapping the Development of Autonomy in Weapons Systems."

information, due both to the comparative size of US defense industry and its relative transparency and accessibility, particularly in comparison to Russia or China.

Munitions

Munitions have the potential to rapidly increase in capability through 2030. Munitions improvements are likely to be driven in part by embedding sensors and computational capability in both ammunition and gun systems to improve performance, but also in response to increasing speed and autonomy in weapons. Additionally, loitering, or persistence, is likely to be a substantial driver in weapon systems, particularly as militaries look to counter specific threats. Competition between states as they seek to develop or maintain military advantages may drive a period of rapid innovation over the next ten years, particularly if tensions between the United States, Russia, and China increase or in the event of great power conflict.

The adoption of hypersonic or directed energy weapons could have a substantial disruptive impact. Russia, China, and the United States are described as leading in the development of hypersonic missiles, which travel at speeds of 6,174 to 12,348 km per hour and could reduce the time from launch to impact of an ICBM strike from Russia to the US from 25 minutes to 6 minutes.[131] Protecting against such high-speed weapons may require directed energy weapons, which Russia, United States, and United Kingdom are

[131] Richard H. Speier, George Nacouzi, Carrie Lee, and Richard M. Moore, *Hypersonic Missile Nonproliferation: Hindering the Spread of a New Class of Weapons* (Santa Monica, CA: RAND Corporation, 2017), accessed 2 April 2019, https://www.rand.org/pubs/research_reports/RR2137.html.

reported to be making substantial investments in research and development,[132] autonomously controlled to identify and engage such munitions. The US Navy has substantially emphasized the importance of directed energy weapons, which have substantial potential in the maritime domain by reducing the magazine requirements of ships.[133] Similarly, directed energy weapons have substantial potential in the air and space domains, which face similar constraints, in addition to the land domain—at least on large vehicles or fixed location where sufficient power is available. Effectively employing directed energy weapons, particularly those traveling at the speed of light, will require substantial autonomy to act at relevant speeds.

Short of the very high-speed, militaries have worked to adopt more sophisticated and capable munitions. The US Army's cancelled XM25 program attempted to develop a man-portable 25mm air-burst grenade launcher; however, the weight and potential safety issues of such a weapon limited its potential utility.[134] More recently, the DARPA's EXACTO program demonstrated the potential to embed guidance systems in ammunition

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[132] Tom Batchelor, "Russia Developing Laser, Electromagnetic and Plasma Weapons, Kremlin Says," *Independent*, 22 January 2017, accessed 2 April 2019, https://www.independent.co.uk/news/world/europe/russia-laser-electromagnetic-plasma-weapons-military-kremlin-a7540716.html.

[133] George Galdorisi, "Unleash Directed-Energy Weapons," *Proceedings* 145, no. 4 (April 2019), accessed 2 April 2019, https://www.usni.org/magazines/proceedings /2019/april/unleash-directed-energy-weapons.

[134] Inspector General, "XM25 Schedule Delays, Cost Increases, and Performance Problems Continue, and Procurement Quantity Not Justified" (redacted), Department of Defense, 29 August 2016, accessed 2 April 2019, https://media.defense.gov/2016/Aug/29 /2001714274/-1/-1/1/DODIG-2016-128.pdf.

as small as a .50 caliber bullet (12.7 mm).[135] Russia, the United States, and various European militaries have adopted or been developing next generation Infantry Fighting Vehicles with main guns in the 40mm to 60mm range; this appears to be substantially driven by the additional guidance, fuse, and other capabilities possible in a larger round.[136] Over the next ten years, it seems likely major militaries will adopt stationary, vehicle mounted, and potentially crew-served weapons with substantial autonomous functioning to improve their effectiveness against a range of targets. Due to weight constraints, and based on the cancelled XM25 program, it seems unlikely that the explosive and guidance capabilities possible in high-caliber ammunition will be achieved in individual soldier weapons, which will likely continue to rely on small-caliber, inert, unguided ammunition through 2030, though weapons may incorporate sensors and computation to greatly improve accuracy—similar to what the US Army has proposed for the Next Generation Squad Weapons.[137] Effectively engaging targets with active protection systems, particularly as such systems continue to improve, may require

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[135] Defense Advanced Research Projects Agency, "EXACTO Guided Bullet Demonstrates Repeatable Performance against Moving Targets."

[136] Samuel Cranny-Evans and Mark Cazalet, "Winning the Firefight: IFV Cannons Evolve," Jane's Defence Industry and Markets Intelligence Centre, 2018; Joseph Trevithick, "One of One of These Big Cannon Toting Armored Vehicles May Replace the Bradley Fighting Vehicle," The Warzone, 8 October 2018, accessed 2 April 2019, https://www.thedrive.com/the-war-zone/24114/one-of-these-big-cannon-toting-armored-vehicles-may-replace-the-bradley-fighting-vehicle.

[137] Army Contracting Command, "Prototype Project Opportunity Notice (PPON) for Next Generation Squad Weapons (NGSW)," Solicitation Number W15QKN19R04OE, Federal Business Opportunities, 20 March 2019, accessed 2 April 2019, https://www.fbo.gov/index?s=opportunity&mode=form&id= 1e061516619fb4b156540d7670296de6&tab=core&_cview=1

munition-based counter measures involving multiple projectiles, stand-off from launching anti-tank missiles (which are at risk from autonomous return-fire capabilities), and autonomous navigation to provide stochastic movement to challenge tracking and interception by active protection systems.

Persistent munitions are also another likely area for rapid development. As discussed in the air domain section, Israel has demonstrated the important role of unmanned loitering munitions for targeting various military radio emission emitters, both radar and electronic warfare systems. Having the capability to autonomously target various emitters in denied environments is likely a critical prerequisite for effective use of remotely operated or manned systems. However, the potential for loitering munitions is not limited to the air domain. Militaries operations in any domains benefit from persistent munitions that autonomously observe the environment and take precise action to counter specific threats. Systems like the Submarine-Launched Mobile Mine, QUICKSTRIKE, or the HAMMERHEAD replacement to the CAPTOR all combine autonomy and mobility to improve mine capability—ironically blurring the early 20th century distinction of mines as stationary and torpedoes as mobile.[138]

Sensors

Improvements in sensor performance, size, and power, along with platforms for fusing multiple sensor modalities will likely be a major driver for improvements in autonomous weapons. Both passive and active sensors have a significant role for

[138] Steve Olsen, "NDIA ExWAR MIW Panel" (23rd Annual Expeditionary Warfare Conference, Annapolis, MD, 16-18 October 2018), accessed 2 April 2019, https://ndia.dtic.mil/2018/expwar/2018expwar.html.

enabling autonomous systems, but potential performance gains are offset by size, weight, cost, power-consumption, and computational requirements. Electro-Optical and Infra-Red cameras will also certainly play a critical role, particularly as computer vision and image recognition capabilities continue to improve. There is also substantial potential for improved target identification and discrimination through fusing multiple sensor modalities and platforms, but to achieve full potential this requires secure communications, which may be particularly difficult in denied environments involving electronic warfare—one of the key use cases for autonomous weapons.

The miniaturization, and commoditization, of key passive sensor systems will continue to be a major driver in technology performance. Electromechanical systems are critical element in modern passive sensors—they are the technology that provides sensors like inertial measurement units (IMUs), magnetometers, and microphones for a wide range of devices, including smartphones, at the scale of a Microelectromechanical Systems (MEMS) are critical enablers to a wide range of consumer electronic and industrial devices, totaling a multi-billion dollar market in 2018.[139] MEMS are currently enabling the ability to automate the aiming of rifles—integrating a range of sensory inputs to remove the need for Soldiers to adjust their point of aim based on range, wind, and atmospheric conditions. The US Army plans to field such a weapon by 2022.[140]

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[139] Technavio, "Global Radio Frequency MEMS Market 2019-2023: Industry Analysis and Forecast," *Business Wire*, 13 February 2019, accessed 3 April 2019, https://www.businesswire.com/news/home/20190213005736/en/.

[140] Jospeh Keller, "The Army's Next-Generation Rifle Will be the iPhone of Lethality, Officials Say," Task and Purpose, 8 February 2019, accessed 3 April 2019, https://taskandpurpose.com/army-next-generation-squad-weapon-iphone-lethality.

Nanoelectromechanical Systems is the next advance in miniaturization, reducing the size, cost, and power requirements of such systems, with current global market estimated to be $11.3 million.[141] Currently leading small commercial MEMS IMUs are on the order of 12x10x4mm, 1g, and consume 16.5mA of current.[142] Some IMUs are subject to International Traffic in Arms Regulations in the United States, and information on high-performance military IMUs may not be publicly available.[143] One application of further miniaturization of electromechanical systems is allowing for them to be embedded in smaller ammunition to enable, for example, guided flight.

Active sensors will also continue to be critical enabler of autonomous weapons. Radar was a critical enabler to some of the early autonomous weapons used in World War II, particularly through the small, short range, Doppler radar used in proximity munitions and in radar systems used for air defense. Lidar originated in the early 1960s, following the invention of the laser, and has rapidly developed to become a widely used sensor, for a range of application including autonomous vehicles, due its ability to provide detailed distance measurements to map the surrounding area.[144] Laser doppler

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[141] Research and Markets, "Applications and Global Markets for Nanoelectromechanical Systems (NEMS)," September 2017, accessed 3 April 2019, https://www.researchandmarkets.com/research/f989rk/applications_and.

[142] Texim Europe, "Ultra Small Robust 6-DOF IMU Weighs Less than 1 Gram," accessed 3 April 2019, https://www.texim-europe.com/news/964.

[143] Honeywell, "Honeywell HGuide Inertial Sensors and Navigators," accessed 3 April 2019, https://aerospace.honeywell.com/en/products/navigation-and-sensors/honeywell-hguide-inertial-sensors-and-navigators.

[144] Ann Neal, "LiDAR vs. RADAR," *Sensors Online*, 24 April 2018, accessed 3 April 2019, https://www.sensorsmag.com/components/lidar-vs-radar.

vibrometers are a similarly powerful active sensor, providing the ability to remotely read vibrations from a wide range of surfaces, allowing the ability to collect, for example, acoustic signals at long ranges.[145] Laser doppler vibrometers have substantial potential to augment target identification capabilities, based on vibration characteristics of particular weapon systems (for example, enemy tank engines). To maximize the potential of such capabilities requires computational power, to do things like target tracking, and to rapidly analyze laser readings to produce usable information.

While performance of individual sensors can provide substantial performance improvements to enable greater autonomy in weapons, the most disruptive potential may be in fusing multiple sensors reading from multiple platforms. Adversaries are likely to try and develop decoys based upon the sensors employed, an effective way to overcome this may be fusing multiple distinct sensory inputs. For example, Anduril's Lattice platform combines multiple sensors to identify objects and provide an integrated view of the operational environment, rather than separate views per sensor modality.[146] Systems that integrate multiple sensor modalities and platforms should be more resilient to decoys, likely substantially raising the cost of decoys. Such systems inherently require secure communications and computation, to integrate multiple sensor modalities, along with necessary power, raising unit costs. However, rapidly integrating multiple sensors is

[145] Rui Li, Tao Wang, Zhigang Zhu, and Wen Xiao, "Vibration Characteristics of Various Surfaces Using an LDV for Long-Range Voice Acquisition," *IEEE Sensors Journal* 11, no. 6 (June 2011): 1415-1422, accessed 2 April 2019, https://ieeexplore.ieee.org/document/5638595.

[146] Anduril, "The Lattice Platform," accessed 3 April 2019, https://www.anduril.com/lattice-ai.

difficult task for human operators and has the potential to greatly improve target detection and identification to provide improved performance that justifies increased cost and complexity of platforms.

Decider

Advances in AI, driven substantially by recent advances in machine learning, seems to have motivated much of the present attention on autonomous weapons. However, algorithmic techniques are only part of the decider aspect; hardware to store data and perform computation, either located onboard with the autonomous weapon or remote, are also critical to the operation of autonomous weapons. These hardware components create trade-offs in performance versus weapon size, power-requirement, cost, and communications-requirements. Choices in decider component design also presents cybersecurity, electronic warfare, and electro-magnetic pulse risks for autonomous weapons.

Autonomous weapons in the cyber domain are a unique case, that are largely excluded from the following analysis on the decider component. Cyber weapons depend upon using computational resources of adversary systems. Accordingly, autonomous cyber weapons are likely to minimize their computational requirements and focus on obfuscation techniques to avoid detection. Given this distinction, the following discussion focuses on the other four domains where an autonomous weapon requires its own computational resources.

While demonstrated advances in machine learning has driven substantial current attention on AI, it may not play such a significant role for autonomous weapons. Machine learning is best suited for problems where there is a massive combinatorial search space, clear objective function to optimize against, and lots of data or an accurate and efficient simulator.[147] That is not the case in many applications for autonomous weapons. First, data availability is greatly limited—potential adversaries are diverse and so are operational environments. Moreover, it will likely be a substantial challenge to develop training data sets for autonomous weapons that are robust to adversarial techniques and can address the wide range of conflicts and potential adversary obfuscation techniques.[148]

Identifying and engaging military targets is often relatively simple, and therefore does not involve a massive search space. Consider, for example, autonomously engaging an incoming missile, a radar emitter, or air-to-air combat; such targets are readily distinguished based on simple sensory inputs, as demonstrated by historical and current weapons that do just that, and the trigonometry to find a firing solution is similarly simple. Certainly, distinguishing some military targets based on sensory inputs does present a large search space, for example, trying to use lidar to distinguish enemy combatants from civilians in urban operations; however, combine lidar with an acoustic gunshot detection system and special awareness of where friendly forces are, then detecting individuals firing upon friendly forces becomes computationally simple. Advances in algorithmic techniques can certainly improve the speed and capability of

[147] Demis Hassabis, "The Power of Self-Learning Systems" (Video, Center for Brains Minds+Machines, 20 March 2019), accessed 3 April 2019, https://cbmm.mit.edu/video/power-self-learning-systems.

[148] Peter Svenmarck, Linus Luotsinen, Mattias Nilsson, and Johan Schubert, "Possibilities and Challenges for Artificial Intelligence in Military Applications" (Proceedings of the NATO Big Data and Artificial Intelligence for Military Decision Making Specialists, NATO Research and Technology Organization, 2018), accessed 3 April 2019, https://www.sto.nato.int/publications/STO%20Meeting%20Proceedings/STO-MP-IST-160/MP-IST-160-S1-5.pdf.

autonomous weapons, but it seems likely advances in hardware, rather than software, may be more relevant for autonomous weapons.

Autonomous weapons could be designed to leverage processor capability across the four major systems architectures: Internet-of-Things edge, cyber-physical systems, mobile, or cloud computing. Cyber-physical systems would allow network communication and computation amongst various systems, for example fusing airborne and ground-based sensor feeds. Cloud architecture systems depend upon data center infrastructure to provide the greatest computation power. Both cyber-physical systems and cloud systems inherently present cybersecurity risks, as these systems depend upon communications channels and dispersed processor potential, and the delays inherent in the communications channels reduce the potential speed of autonomous weapons—one of their key relative capabilities to manned or remotely operated weapons. Autonomous weapons with a cloud architecture is also inherently adaptable from a weapon remotely operated by a human, as such systems must have well-defined interfaces and communication channels for remote operation.

To avoid dependence on communications links, mobile and Internet-of-Things edge architectures may be preferable systems for many autonomous weapons. Internet-of-Things edge architectures deliver the least processor capability but have the least power and size requirements, making it suitable for purposes like autonomously guided ammunition, man-portable systems, loitering or persistent munitions that operate for durations on the scale of weeks and months. Mobile architectures require ongoing power generation or depend on stored energy, presenting a size and weight requirements likely best suiting them to vehicle mounted autonomous weapons or autonomous weapons that only require operational time on the order of hours or days.

All four systems architecture are likely to see exponential rate of processor performance improvements through 2030. The 2017 International Roadmap for Devices and Systems predicts that three-dimensional integrated circuit structures will allow continuation of Moore's Law rate of processor performance improvement.[149] However, it notes thermal characteristics and power consumption will be an increasingly significant market driver—this is likely particularly the case for autonomous weapons. Thermal output increases the infrared signature of a weapon and the power consumption increases the size and weight of systems. Application Specific Integrated Circuits may be particularly appropriate for autonomous weapons as they are generally able to provide greater computational performance relative to power and thermal output; for example, Intel's Myriad X provides substantial performance for image recognition while requiring only 1.5 watts.[150] Some simple autonomous functions, like detonating a munition based on a magnetometer reading, do not require complex computation and may be best delivered through discrete, analogue circuits rather than digital computation.

Onboard computation is likely to be the key enabler of advanced autonomous weapons. Systems that depend on remote computation can readily be remotely operated, and are less viable for operating in denied environments, performing at very high speeds,

[149] The Institute of Electrical and Electronics Engineers, "International Roadmap for Devices and Systems 2017," accessed 3 April 2019, https://irds.ieee.org/roadmap-2017.

[150] Intel, "Intel® Movidius™ Myriad™ X VPU," accessed 3 April 2019, https://www.movidius.com/myriadx.

and are vulnerable to detection and security risks due to their dependency on communications to remote computation. Key computational tasks of autonomous weapons are not complex—nothing is complex about detonating an air-burst munition at the right location to a target. The most difficult tasks autonomous weapons are likely to perform are object recognition and navigation in complex terrain using multiple sensory inputs—the adoption of autonomous weapons that perform those tasks are likely to follow adoption of weapons that perform simpler computational tasks. Therefore, the key enabler of autonomous weapons over the near-term is likely to be providing the minimal necessary computational performance at low cost and at a small size, low thermal output, and low power consumption to enabled embedded applications on weapons like loitering munitions, anti-tank missiles, and naval mines.

Power

Power is likely to be one of the key constraints on the performance of autonomous weapons. Autonomous weapons, depending on their specific use-cases and requirements will involve some mix of measures for stored energy, energy harvesting, energy production, and external power. Additionally, autonomous weapons can employ a variety of measures to improve their energy efficiency. For example, a naval mine may use a highly efficient passive acoustic sensor to trigger an active sensor to identify a target.

Stored energy can take multiple forms and may be sufficient to support some autonomous systems for extended periods. Electrical energy may be needed to power various circuits, sensors, or solid-state lasers and can readily be stored in a capacitor or battery. Various chemical storage is common, explosives are used in most modern autonomous weapons. Similarly, mechanical storage may be used, for example compressing a spring. The principal trade-offs in stored energy solutions is size, weight, cost, duration, and reliability relative to energy provided.

Energy harvesting is likely to be a key technique for small autonomous weapons, embedded systems, passive sensors, and space systems. Energy harvesting depends upon capturing energy from motion and ambient sources to power their systems. For example, ammunition with autonomous functions can derive power from its ballistic flight to support those. Similarly, passive sensors can be viewed as externally-powered systems—where the signal produced by the sensor is derived from the acoustic wave, magnetic field, or radio signal effecting the device. Various forms of ambient energy can also be used, for example solar, wind, or wave motion. Spacecraft usually use of photovoltaic solar panels to power their operation. Likewise, systems in other domains can be powered by ambient energy prevalent in their operational environment. Some autonomous systems, with lower power requirements, may be able to operate for years by using just harvested ambient energy.

Larger autonomous systems, particularly mobile systems, may have greater power requirements and therefore be dependent on energy generation. Radioisotope thermoelectric generators have long been used in spacecraft and a reliable source of power for systems that operate for multiple decades. On the scale of multiple years duration, small fuel cells are a highly reliable power source able to provide on the order of 500 Watt-hour per kilogram, a large improvement over the 44 Watt-hour per kilogram possible from lithium ion batteries.[151] For mobile systems in the air and land domain, that operate for periods on the order of hours and days, internal combustion engines are likely to continue to be the predominate source of energy. Meanwhile, stationary systems in the land domain, like sentry guns, may use external power with only limited onboard back-up storage or generation in case of power disruptions.

How an autonomous weapon is powered is likely to be highly dependent on the intended use case and the domain it operates in. Reducing power requirements is likely to be a significant engineering focus, in order to reduce the size and weight of the system, while providing it increased persistence. Militaries are likely to seek autonomous weapons that can operate on harvested energy with small reserves of stored energy; however, for larger, more powerful, and mobile systems this will not be possible, and instead an energy generation solution will be selected that reliably provides sufficient power while minimizing the weapon's detection signature, size, weight, and cost.

Mobility

Mobility is a key distinguishing factor of autonomous weapons, and one that may constrain autonomous weapon use in the land domain. Autonomous weapons may be stationary or mobile, and they may autonomously move, or their movement may be controlled by a user. An Active Protection System, like Trophy, is stationary relative to the vehicle it is mounted on, but that vehicle may be manned or remotely operated and move about the battlefield under the full control of a user. Space, Air, Maritime, and

[151] C. K. Dyer, "Fuel Cells for Portable Applications," *Journal of Power Sources* 106, no. 1-2 (April 2002): 31-34, accessed 3 April 2019, http://adsabs.harvard.edu /abs/2002JPS...106...31D.

Cyberspace domains are less cluttered than the land domain and therefore easier for autonomous movement, accordingly the land domain is likely to lag the other domains in adopting autonomously mobile systems.

Autonomous weapons will likely be fielded with highly variable speed from stationary to hypersonic. Greater speed generally makes a weapon more effective and the ability to act at high speeds is likely to be one of the key motivating capabilities driving the adoption of autonomous weapons. However, persistence in performing mundane tasks, like observing a designated area, is another key motivating capability for use of autonomous weapons—providing that persistence may require use of stationary or very slow systems in-order to reduce power requirements. Accordingly, autonomous weapons will operate across a full range of speeds from the stationary, but persistent for years, to the very high-speed but short duration. Figure 2 illustrates the likely preference for autonomous weapons in circumstances that require long endurance or quick reactions.

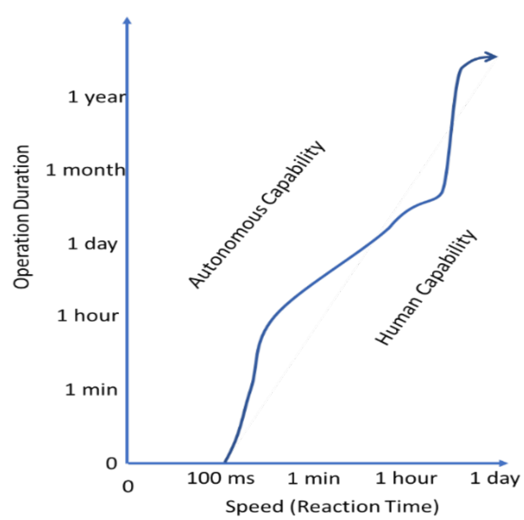

Figure 2. Autonomous vs Human Capability Relative to Time

Source: Created by author.

Communication

Communications systems could take many forms, but regardless of form is a critical element that effects the selection between autonomous and remotely operated weapons and shapes the vulnerability of the weapon to electronic warfare and cyber operations. Some simple and expendable autonomous weapons, like mines, may have no communication system, but it seems likely communications will commonly be integrated into autonomous weapons. Other systems could operate asynchronously and require physical access—for example, following a mission allowing for download of mission data, diagnostics, or adjustments to software or configuration settings. Communications used will also reflect the domain and operational environments the weapon is used in—for example, undersea systems are likely to continue to use acoustics for communication. However, it seems likely militaries will integrate some form of remote communications into autonomous weapons to allow for status monitoring, the fusing of multiple discreet sensor platforms, remote computation, and for some form of remote control.

The presence of a communication system that allows for remote control exists in some tension with the notion of an autonomy; however, it is not a contradiction. Control over the use of force is fundamental to the purpose militaries. Accordingly, militaries are likely to design autonomous weapon to provide for supervision and ability to adjust the tasks autonomous weapons are executing in order to provide this control. Even with some degree of control, a weapon may execute its harm-causing function autonomously based on independent action in response to sensory inputs. As previously discussed, a weapon can be both remotely operated and autonomous; for example, a remotely piloted aircraft could be designed to autonomously attack the source of a signal jamming its communications.

Ensuring the confidentiality, integrity, and availability of this communications channel to the autonomous weapon will be a key design challenge. A full range of cybersecurity and communications security measures are likely to be used. Communications are likely to be encrypted. Relatively short-range, line-of-sight systems may be employed in a range of autonomous weapons, for example in aerial teaming concepts, to reduce the risks related to the communications channels. However, despite these security measures there will likely be some residual risks. This residual risk also exists for any remotely operated system, and these common risks will likely be a powerful motivation for militaries to make remotely operated systems increasingly autonomous.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Will robots inherit the earth? Yes, but they will be our children.
— Marvin Minsky, "Will Robots Inherit the Earth?"

Militaries have long used weapons with autonomous capabilities and are likely to increasingly use autonomous weapons as their effectiveness is demonstrated. Autonomous weapons predate remotely operated weapons in most domains. The air domain is instructive in this regard, as the invention of television in the 1930s disrupted prior work on more autonomous aircraft by allowing for the remote operation of aircraft out of sight from the pilot. Remotely operated systems are likely to continue to be generally preferred by militaries, but those systems will have increasingly autonomous capabilities, particularly in targeting enemy systems that disrupt their command and control links. This suggests rather than viewing "autonomous weapons" as a distinct class of systems, instead we should consider the autonomous capabilities of a weapon and how it is controlled by its user.

Correctly considering autonomy in weapons begins with recognizing weapons are tools, and like all tools have a user. "Full autonomy," in the sense of absolute independence, is not a desirable property of a tool. Rather, users will maintain some control over their tools to ensure they are accomplishing their desired purpose. Instead of trying to distinguish between what is autonomous and what is not, we should focus on the relationship between the user and the tool. To paraphrase David Mindell: "Where are the [users]? Who are they? What are they doing? When? Why does it matter?"[152] Unencumbered with trying to distinguish between what is autonomous and non-autonomous allows analysis to instead focus on autonomy in executing particular functions.

Recognizing militaries have long used autonomous weapons makes predicting their future use a matter of identifying the capabilities militaries have sought to achieve through autonomous weapons in the past, and how technology is changing what is possible. Considering this history, autonomous weapons have predominately been used to address at least one of four challenges: the mundane, the fast, the denied, and mass. Autonomous weapons aid militaries in addressing the mundane, or long duration, by providing greater persistence in observing and reacting to events over an extended period than is efficiently achieved with a manned system. In terms of both reaction speed and at high accelerations, autonomous weapons can operate at speeds exceeding what people are capable of. A particularly attractive feature of autonomous weapons is the ability to operate in denied environment, either due to environmental conditions or enemy action, that present unacceptable risk to manned systems or to the control channels for remotely operated systems. Finally, autonomous weapons provide increased mass, like most any military technology, by increasing the military power of a state relative to its available population for military service.

Technology change over the next ten years is steadily going to improve performance potential of autonomous weapons. Improvements in sensors and power

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[152] David Mindell, *Our Robots, Ourselves: Robotics and the Myths of Autonomy* (New York: Viking Press, 2015), 225.

performance seem to be the critical element that will enable more capable autonomous weapons, particularly for addressing the mundane and the fast. Meanwhile the adoption of faster weapons (for example, hypersonics, and directed energy) and increased contesting of communications channels will be a substantial driver for militaries to increase the autonomy of weapon systems. Advances in AI and computer performance will certainly improve autonomous weapons performance in the cluttered and complex land domain, but in other domains may not be as significant a factor as is commonly imaged. Rather improved power efficiency, low-cost, and increased reliability is likely more significant than computational performance for a wide range of autonomous weapons.

Country variance in adoption of autonomous weapons is a potential area for future study. Some key technological components of autonomous weapons, like IMUs, are subject to export control regimes; however, many of the components of autonomous weapons are likely to be globally available as autonomy is adopted for a wide range of commercial applications. The particular security challenges countries face may be the most significant element in driving military use of autonomous weapons. Autonomous weapons allow states to turn their economic potential into military capability with greater independence from its available population for military service. Accordingly, military expenditure per capita may be a reasonable predictor of countries that will be leading adopters of autonomous weapons. The ten countries with the highest per capita military expenditure are listed in table 1.

Table 1. The Ten Countries with Highest Military Expenditure per Capita

Country Name	Military expenditure (2017, $) per capita
Saudi Arabia	$2,107.38
Israel	$1,892.59
Oman	$1,873.62
United States	$1,872.04
Singapore	$1,817.17
United Arab Emirates	$1,807.10
Kuwait	$1,651.41
Norway	$1,243.43
Australia	$1,116.40
Bahrain	$ 935.83

Source: The World Bank, "World Bank Open Data," accessed 10 April 2019, https://data.worldbank.org/indicator/MS.MIL.XPND.CD.

Further research is needed on how autonomous weapons are likely to change the nature and character of future conflicts. How does the increasing use of, and performance of, autonomous weapons effect the state's ability to monopolize the legitimate use of force? Is human enmity, hatred, and passion as an element of war reduced by use of autonomous weapons thereby allowing for greater control of conflict? How does increasing use of autonomous weapons alter strategy—are wars that are fought substantially with autonomous weapons likely to be wars of attrition or wars of annihilation? The potential speed of autonomous weapons suggests wars of annihilation, but the role of autonomous weapons in providing mass, and associated economic dependencies, suggests attrition. The answer to this question shapes the sort of autonomous weapons nations develop—high performance in the case of wars of annihilation or cost efficient in the case of wars of attrition.

As autonomous capabilities improve, militaries are likely to encounter challenges in effectively integrating them with manned systems. Militaries are likely to use weapons that act with varying autonomy depending on the circumstance. It will be a substantial design challenge to create systems that can smoothly transition from human control to autonomous machine control and from autonomous control to human control. Addressing this challenge requires recognizing autonomous weapons are not a distinct class, rather future weapon systems are likely to have a wide range of functions that are autonomously executed in varying circumstances.

Providing for human control of weapons requires having capabilities to contest adversarial ability to deny that control. Remote weapon operation requires a secure communication channel, but as militaries develop increasing cyber and electronic warfare capabilities that communication channel is put at risk. Autonomous weapons are likely a key countermeasure to target and destroy adversary systems that put communications systems at risk. Developing and fielding autonomous emission-seeking loitering munitions to target and destroy adversary electronic warfare capabilities will likely be a high priority for all militaries.

The normative and ethical considerations related to autonomous weapons are an area that needs further research. Existing literature on the ethics of autonomous weapons tends to describe them as a potential future capability not an existing capability, which may create a status quo bias in arguing against autonomous weapons. It also appears a substantial element in some moral arguments against autonomous weapons is a reaction to a challenge in what it means to be human. There seems to be a deeply held moral intuition that humans ought to have control over killing other humans. Autonomous weapons may be a key means for providing for that control, for example by targeting systems to disrupt command and control channels. If autonomous weapons are seen not as a means to kill humans, but as a means to target adversarial military systems that undermine control over who is killed, I suspect it fundamentally alters normative perspectives. It also suggests rather than seeking to ban autonomous weapons, to seek banning electronic warfare and other systems that erode control over the use of force.

Autonomous weapons seem likely to be increasingly used by militaries, with the pace of adoption likely driven both by demonstrated performance and the particular security circumstance of a state. However, rather than fully independent autonomous weapons, militaries are more likely to use remotely operated weapons that have increasing autonomous functions, including over aspects closely related to causing harm. While a wide range of questions remain to be answers on the effect of this change, it seems critical to recognize the interplay between remotely operated and autonomous systems. Both from a design perspective, but also from a competition and stability perspective—that is adoption of capabilities to disrupt command and control channels is likely to drive increasing autonomy. In this role, autonomy may be a solution to providing greater control over the use of force, rather than a threat to that control as it is popularly perceived. Autonomy in weapon systems provide assurance of their continued function even if control channels are disrupted, thereby deterring such disruption and allowing for more discriminate weapon performance even in the absence of immediate human control.

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