Learning from the Ukrainian Battlefield: Tomorrow's Drone Warfare, Today's Innovation Challenge

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Learning from the Ukrainian Battlefield: Tomorrow's Drone Warfare, Today's Innovation Challenge

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Content

Executive Summary

Russia's war in Ukraine has undoubtedly become the single most important conflict for understanding how drone warfare may take shape in the future. This research report identifies nine key takeaways based upon a comprehensive analysis of combat-proven practices from the Ukrainian battlefield. These lessons cover technology, doctrine, and policy alike. The report's four chapters examine the main opportunities for improving drone capabilities across functions and operational domains. They also highlight the persistent challenges accompanying the development, integration, and deployment of new uncrewed systems. Importantly, however, drones are not a panacea for achieving strategic victories or winning wars. This report therefore makes an effort to manage expectations about drone capabilities while emphasizing the central role of human capital. Indeed, when combined with new enabling technologies, skilled specialists produce effective drone performance.

Chapter 1 analyzes drone warfare by both sides in the war in Ukraine. Past drone wars featured large, long-endurance drones equipped with powerful sensors and loaded with missiles. But in post-2/22 Ukraine, drone diversity dominates the battlefield. Drones, small, inexpensive, and commercially available, demonstrate their tactical utility in high-intensity warfare by both providing a live-feed of the battlefield and becoming ammunition themselves. These developments have contributed to an improved cost-per-effect ratio of drone capabilities and an increasing relevance of vertical dimensions in land operations.

Chapter 2 covers the diffusion of drone technology. Unsurprisingly, new national acquisition strategies are slowly embracing drone diversity. This includes not only surveillance drones of different sizes but also drones armed with anti-armor bombs, as well as loitering munitions. And while the popularity of commercial small drone technology solutions keeps rising among militaries, large surveillance drones have gained new customers thanks to their comparative strategic advantages. However, countering drone threats presents a persistent problem for modern militaries.

Chapter 3 examines drone research and development. Military artificial intelligence (AI) is continuously enhancing data analytics and command and control. Yet, it continues to face issues with reliability and effectiveness. Drone wingmen teamed with humans define next-generation uncrewed systems. Meanwhile, aerial drones coordinate with uncrewed – and increasingly weaponized – ground vehicles and drone boats in multi-domain operations.

Finally, Chapter 4 highlights the innovation adoption challenge that can seriously impede successful integration of new drone systems into military force structures. It highlights two further policy problems likely to shape future drone warfare: obsolete export control standards leading to eased proliferation of drones to hostile actors, and insufficient legal and ethical norms addressing experiments with AI on active battlefields.

Key Takeaways

Technology

1. Small-sized drones and long-range loitering munitions increase airborne diversity on the battlefield.

2. Inexpensive and commercially available technology is a key enabler of rapid innovation cycles on the battlefield.

3. Drones operate with greater levels of autonomy thanks to AI-powered systems and interconnected data architecture.

Doctrine

4. Drone warfare is spreading across the air, sea, and land domains, and is enabled by the space and cyber domains.

5. Decreasing the cost of drone countermeasures and coordinating air defense across mobile force units are essential to countering small drones *en masse*.

6. Interactions between a human and a machine are becoming integral to warfare, yet human–machine teaming still poses important challenges.

Policy

7. Successful adoption of emerging drone capabilities requires investments into human skills, interoperability, scalable commercial solutions, and resilient communication networks.

8. Accessible drone technology has accelerated experimenting with military AI under conditions of ambiguous ethical and legal standards.

9. The lack of multilateral export controls and a global trade compliance program facilitates drone proliferation to hostile actors.

Introduction to Drone Technology and Warfare

Since Turkish Bayraktar drones were first used against Russian convoys advancing on Kyiv in February 2022, thousands of small flying scouts scanning the battleground have become a daily reality in Ukraine. Drone functions and operations on the battlefields of Ukraine are undeniably evolving. Today, barrages of loitering munitions continue to target the Ukrainian energy infrastructure, and videos of bombs dropping into tank turrets from the sky inundate social media. Thus, it has become impossible to overlook the growing importance of drones in contemporary warfare.

Drones, or uncrewed aerial systems, are far from a new technology. In fact, drones are as old as aviation and airpower itself. Austria used incendiary balloons to attack Venice in 1849. The early 1900s saw balloons controlled from afar by basic radio transmitters. Both of these weapons can justifiably be referred to as the first crude, pilotless aerial systems.[1] The predecessors of today's armed drones, such as the US Kettering Bug, were developed during the First World War. But drones were never directly used on the battlefield until Israeli operations using loitering munitions in the 1980s. Drones had been deployed in warfare previously though. In the 1930s and 1940s, drones were able to collect intelligence due to remote radio-controllers and rudimentary camera systems for aerial photography. Drone developments then accelerated during the Vietnam and Iran–Iraq Wars.

The modern drone era did not begin until the 1990s, despite earlier, sporadic examples of uncrewed aerial systems and their use by militaries. This is mostly because sensors and communication systems matured and became more reliable. The maturation of modern drone technology can subsequently be identified with three main time periods, or ages.[2]

First Drone Age

In the 1990s through the 2010s, drones were mostly conceived of as advanced large airborne platforms. These ensured persistent surveillance and conducting precision strikes. The first real-time transmission of video by the American Predator drone, deployed in Bosnia in 1994, accordingly marks the beginning of the First Drone Age. This was soon followed by the first drone strike during Operation Enduring Freedom in Afghanistan in 2001.

Drones of this era came in two Class III variants: medium-altitude, long-endurance (MALE); and high-altitude, long-endurance (HALE) drones. Both types carried either intelligence, surveillance, and reconnaissance (ISR) sensors, or weapons. Drones thus became enablers of remote warfare that allowed risk-averse political leaders to avoid sending "boots on the ground" by fighting terrorism from afar. Those large drones were deployed in areas where the technologically superior side controlled the airspace and could fly large aircraft to scan theater-wide areas for extended periods of time. This increased the remoteness of warfare. In addition to these large drones operated through space-based satellite links, military drone technology of the era also included smaller vehicles. Class I drones, resembling spy gadgets, are a category that include aircraft that can fly for 20 minutes and fit in the palm of one's hand or small, hand-launched model planes used for local reconnaissance. Class II aircraft are mid-sized tactical drones with ranges that extend beyond the line of sight, weighing between 150kg – 600kg. These drones require a catapult to be lifted into the air.

Another type of airborne uncrewed vehicle, somewhat of a cross between a drone and a missile, has also given ground forces more precise strike capabilities than mortars or rockets. Loitering munitions are designed to engage the target beyond the line of sight with an explosive warhead that detonates on impact. These drones can stay loitering in the air for some time before striking their target and often feature high-resolution electro-optical and infrared cameras. Perhaps the most famous loitering munition, the Israeli Harpy from the 1990s, proved effective in destroying radar installations and mobile missile launchers.

Second Drone Age

Vertical (new tech) and horizontal proliferation (new actors) of drones define the Second Drone Age. For roughly thirty years, military drones were the exclusive tools of the most advanced armed forces, with Israel and the United States as the first movers in modern military drone technology. However, the past two decades have witnessed the spread of drones into the hands of a wider array of less-resourced countries, non-state militias, and even terrorist groups. They have also been deployed to assist international humanitarian missions. The global drone market has therefore expanded thanks to the rise of new exporters, such as China, Iran, and Turkey. These

[1] Sarah E. Kreps, 2016, Drones: What Everyone Needs to Know, Oxford University Press, 9.

[2] James Patton Rogers, ed., 2024, De Gruyter Handbook of Drone Warfare, De Gruyter.

proliferation dynamics have altered cost and risk calculations about drone use in conflicts.[3]

Importantly, the exponential development of small and inexpensive consumer-grade drones in the early 2010s has accelerated these proliferation trends. Commercial hobbyist drone technology, together with the introduction of smartphones that provide easily obtainable control devices and sensors, has lowered the entry barriers in terms of platform costs and supporting infrastructure for accessing airpower assets.[4] This accessibility of technology has contributed to now exponential increases in drone popularity.

Furthermore, traditional air defenses face difficulties countering small commercial drones. Due to their material composition and flying altitudes, as well as multirotor propulsion which makes them difficult to detect and intercept, these drone characteristics allow various military groups to "punch above their weight". Drones have the potential to enable such groups to cause military effects that are disproportionate with their limited resources.

Third Drone Age

Finally, the new era in drone warfare is distinguished by continuing proliferation of drone technology not only to new state and non-state actors, but also across operational domains. Multiple fast-paced technological advances – especially the advent of AI-enabled autonomy and transparency of the digital battlefield – are moving these systems into the Third Drone Age. However, this age is unfolding in a security environment characterized by increased uncertainty and permeability, with new weapon systems assuming their function as political bargaining chips, rather than military assets. [5]

The ongoing war in Ukraine illustrates this gradual transition from the Second to the Third Drone Age on a single battlefield. In the previous eras, the rationale for using drones was to avoid deploying troops on the ground and into potentially hazardous zones. Prior to Russia's war in Ukraine, drones were thought to be most useful in conflicts where one side maintains air superiority, that is, to replace boots on the ground. In Ukraine, however, drones have boots. [6] In other words, drones can help soldiers down to the lowest level on the field.

The stark contrast with previous drone ages is remarkable. Large armed and surveillance drones are less in demand as inexpensive commercial drone technology is improving cost-per-effect in combat, bringing verticality into land operations, and empowering individual soldiers and improving their situational awareness.[7] In Ukraine, drones have become cost-saving agents that reduce expenditures by enabling cheap delivery of explosives. [8]

Furthermore, in the maritime domain, Ukraine has mounted remarkable drone boat campaigns against the Russian Black Sea Fleet.[9] Awhile Russian ground drones have tried to open a new drone front.[10]

There are also other clear implications for emerging and disruptive technologies. Importantly, the war in Ukraine shows how the convergence of a great amount of data – thanks to open-source personal devices, high-speed internet connectivity, and commercial geospatial intelligence – and fast-advancing microchips have created fertile grounds for an AI gold rush.[11] Integrating automated, autonomous, and AI-powered software into military decision-making processes and weapon systems has turned the battlefield into an experimental lab. These activities steadily contribute to the rise of algorithmic warfare.[12]

This research report accordingly investigates the recent developments in drone technology and doctrinal adaptation across the air, land, and maritime (surface and underwater) operational domains. It also discusses the enabling domains of space and cyber. With the Ukrainian battlefield as its backdrop, the report's four chapters map current trends in uncrewed systems and resultant countermeasures. The chapters reflect on future drone capabilities and identify their implications for both warfare and policy.

This report relies on the author's examination of open-source databases, materials, and observations from war correspondents. Furthermore, the author consulted the most up-to-date analyses by the community of drone experts and also compiled press and news media reporting on drones. Despite representing a single conflict zone, Russia's war in Ukraine – the first large-scale drone war – presents an extraordinary analytical case. In addition to home-grown drone production, the imports of

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3 Michael J. Boyle, 2020, The Drone Age: How Drone Technology Will Change War and Peace, Oxford University Press.

4 Audrey Kurth Cronin, 2019, Power to the People: How Open Technological Innovation Is Arming Tomorrow's Terrorists, Oxford University Press.

5 Alexander K. Bollfrass and Stephen Herzog, 2022, "The War in Ukraine and Global Nuclear Order", Survival 64(4), 17.

6 Dominika Kunertova, 2023, "Drones Have Boots: Learning from Russia's War in Ukraine", Contemporary Security Policy 44(4), 576–591.

7 Dominika Kunertova, 2023, "The War in Ukraine Shows the Game-Changing Effect of Drones Depends on the Game", Bulletin of the Atomic Scientists 79(2), 95–102.

8 Jacquelyn Schneider, 2023, "Unscorable at 12: Technically Correct, but Misses the Mark", Security Studies 32(3), 568–574.

9 Steven Wills, 2024, "Sea Drone Swarms – Can NATO's Navies Avoid Russia's Fate?", Center for European Policy Analysis, March 6, https://cepa.org/article/sea-drone-swarms-can-nato-navies-avoid-russias-fate

10 Amos Chapple, 2024, "Ground Drones: The Next Frontier of Unmanned Combat In Ukraine", Radio Free Europe, April 18, https://www.rferl.org/a/ground-drones-war-russia-invasion-ukraine/32911118.html

11 Dominika Kunertova and Stephen Herzog, 2024, "Emerging and Disruptive Technologies Transform, but Do Not Lift, the Fog of War: Evidence from Russia's War on Ukraine", Finnish National Defence University.

12 Ingvild Bode, Hendrik Huelss, Anna Nadibaidze, Guangyu Qiao-Franco, and Tom F. A. Watts, 2024, "Algorithmic Warfare: Taking Stock of a Research Programme", Global Society 38(1), 1–23.

foreign military drones[13] and introduction of uncrewed systems into other operational domains – namely, drone boats and ground robotic vehicles – are making Ukraine a true in-field testbed for the deployment and use of new uncrewed weapons systems.

1 Drone Warfare in Ukraine

Russia's war in Ukraine has shown that the Second Drone Age is far from over and is still actively shaping dynamics on the battlefield. Several short-term drone developments taking advantage of relatively simple designs and low costs have led to important and fast tactical effects, even under the conditions of contested airspace.[14] This chapter therefore maps the variety of drone systems deployed in Ukraine across all main drone classes. However, despite these innovations, drones are not a war-winning capability. To explain why, the second section outlines five main limitations of the current generation of drones.

1.1 Drone Strength in Diversity

This section presents the advantages of drone use in terms of platform diversity and costs across various levels of military command hierarchy. At the lowest echelons (the squad, platoon, and company levels), troops are using small commercial quadcopter drones. These are either assembled from commercially available parts or hobbyist toys bought directly on the internet for a few hundred USD that are often fundraised or donated by private civilians at home and abroad.[15] Weaponized with hand grenades, mortar shells, or anti-tank missiles, these repurposed commercial Class I drones have become anti-personnel and anti-tank/armor vehicles weapons in the form of makeshift guided ammunition with variable accuracy.

These small drone tactics date back to separatist fighting in Eastern Ukraine after the first Russian invasion in 2014. While the rebels deployed drones carrying Russian-made Termite grenades, Ukrainian volunteer forces used commercial drones for gathering intelligence and attacking rebel positions.[16] Since 2022, the scale of drone deployment has become unprecedented. Russia's war in Ukraine has led to exponential developments in Class I drones under 150kg (see Table 1). As a result of their user-friendliness, low cost, and connection via space-based internet, Ukrainian soldiers were able to deploy small drones for reconnaissance and dropping hand grenades on targets *by the thousands*.

The Chinese-made DJI Mavic quadcopter is the most widely used model. With their optical sensors and the ability to stay in the air for almost 50 minutes at altitudes of up to 6km, these drones help troops monitor the battleground from above and track their adversary's troops. They can also record explosion events for future lessons-learned and sharing with traditional and new media outlets. In October 2023, Ukraine was buying 60% of DJI's global production of Mavic quadcopters. This is quite an astonishing number since DJI accounts for 90% of the global market in commercial drones. These drones are available on Alibaba, AliExpress, and Amazon, with prices ranging from a few hundred up to a few thousand USD, depending on the type of camera and interface. Kyiv and its supporters are hardly the only ones in this conflict interested in Chinese drone technology, of course. Russia received drone equipment from China worth over 14.5 million USD during the first half of 2023.[17]

Similarly, first-person-view (FPV) drones, a commercial version of military loitering munition, have been dubbed the ultimate asymmetric weapon, much like David's sling against Goliath's sword. These one-way attack drones behave like disposable ammunition that can loiter prior to crashing into their target. They may cost as little as 400 USD. In contrast, military-grade loitering munitions are more expensive. For example, the cost of the US-made Switchblade-300 loitering munition and Russia's

13 For instance, the United States delivered Switchblade-300 and Ghost Phoenix loitering munitions to Ukraine while Poland offered its Warmates. Ukraine's pre-war arsenal included Bayraktar TB2 drones from Turkey. Russia secured imports of Mohajer 6 and Shahed-136 drones from Iran.

14 Marc DeVore, 2023, "'No End of a Lesson:' Observations from the First High-Intensity Drone War", Defense & Security Analysis 39(2), 263–266.

15 At the grassroots level, civilians have raised resources through crowdfunding to buy drones for Ukrainian fighters, such as the Latvian campaign to purchase Turkish Bayraktar drones. In other cases, companies delivering drones are compensated by their respective national governments. Quantum Systems, funded by the German government, delivered mid-range Vector surveillance drones to Ukraine. Slovenia's government also financed the export of the surveillance drone system Belin, made by drone manufacturer C-Astral. See: Elisabeth Gosselin-Malo, 2024, "German Drone Maker Helps Ukrainian Forces Own the Night", Defense News, January 23, https://www.defensenews.com/global/europe/2024/01/23/german-drone-maker-helps-ukrainian-forces-own-the-night; Elisabeth Gosselin-Malo, 2023, "Slovenian Firm Quietly Provides Surveillance Drones to Ukraine", Defense News, October 26, https://www.defensenews.com/unmanned/2023/10/26/slovenian-firm-quietly-provided-surveillance-drones-to-ukraine

16 Matt Burgess, 2022, "Small Drones are Giving Ukraine an Unprecedented Edge", Wired, May 6, https://www.wired.com/story/drones-russia-ukraine-war

17 Elisabeth Gosselin-Malo, 2023, "Ukraine Continues to Snap up Chinese DJI Drones for Its Defense", C4ISRNet, October 23, https://www.c4isrnet.com/global/europe/2023/10/23/ukraine-continues-to-snap-up-chinese-dji-drones-for-its-defense

ZALA Lancet loitering munition (including its cheaper version, Scalpel) may run buyers from 35,000 to 50,000 USD apiece.

This type of cheap, human-guided munition has many notable elements. These include real-time video transmission to its operator, first-person control that enables precision and responsive maneuvers, and a compact size suitable for diverse environments.[18] Over summer and autumn 2023, the production of FPV drones increased in both Ukraine and Russia, reaching several thousand vehicles per month. Crucially, these one-way attack drones turn conventional air campaign logic on its head. The drone platform itself – in this case non-recoverable, attritable, and replaceable – matters far less than its one-way effects.

The popularity and versatility of drone capabilities led Ukraine's government to launch the Army of Drones project to facilitate drone innovation. Focus areas under this umbrella range from pure ISR platforms to those for use in diverse combat drones. The stated goal is to produce up to two million drones in 2024. Though Russia has prioritized manufacturing military-grade drones in the past, it has almost caught up with Ukraine in conducting strikes with commercially available racing drones.[19]

At the brigade and battalion level, troops tend to use catapult-launched, fixed-wing Class II drones for long-range reconnaissance or one-way attack strikes. These drones often significantly enhance target acquisition for artillery due to their range. Their cost, however, can be prohibitive, as it often reaches 80,000 to 100,000 USD. But with this sort of drone intelligence on hand, the time between the detection of an enemy and an attack can be reduced to a mere three minutes in some cases.

Russia uses long-range Shahed-136 loitering munitions in addition to operating Orlan-10, or more recently, SuperCam S350s reconnaissance drones. The Shahed drone is manufactured and imported from Iran. Dozens of Russian-operated Shaheds have attacked Ukrainian cities and damaged critical infrastructure, such as electricity grids. While Ukrainian air defenses intercept Shaheds at a rate of more than 80%, the cost to Ukraine of defending against these drone threats is incomparably higher than the cost of the weapons is to Russia. The low cost of these loitering munitions (20,000 to 50,000 USD

Table 1: Drone Diversity in Ukraine

Class	Category	Weight (kg)	Operating Altitudes (feet)	Ukrainian Operations	Russian Operations
Class III	HALE	>600	>65,000		
	MALE /Combat		<45,000	Bayraktar TB2	Forpost Orion
Class II	Tactical	<600	<18,000	UJ-22 UJ-23 Topaz UJ-26 Beaver	Shahed-136 Orlan-10 SuperCam S350s
Class I	Small	<150	<5,000	Baba Yaga Switchblade-600	SCAT 350s Eleron T-16
	Mini	<15	<3,000	DJI Mavic DJI Phantom R 18 HERO-120 Switchblade-300 Warmate Saker Scout FPV drones	DJI Mavic DJI Phantom DJI Matrice 300 ZALA Lancet Ovod FPV drones
	Micro	0 – 2	<200	DJI Mini	DJI Mini

18 Paul Schwennensen, 2024, "Drones and Asymmetric Warfare in Ukraine and Israel", Geopolitical Intelligence Services, February 20, https://www.gisreportsonline.com/r/drones-ukraine-israel

19 Roman Vysochanskyy, 2024, "Redefining the Battlefield: Drone Warfare Tactics in Ukraine", Project Ploughshares, February 27, https://www.ploughshares.ca/publications/redefining-the-battlefield-drone-warfare-tactics-in-ukraine

per unit) contrasts with 500,000 USD AMRAAM and IRIS-T missiles, or multi-million USD Patriot surface-to-air missiles. To counter this disadvantage and reduce the danger of depleting stocks of air defense missiles, Ukraine's countermeasures also include anti-aircraft guns.

Russia has also begun to produce the Shahed locally for cost-related reasons. In 2023, its 2 billion USD weapons deal with Iran involved technology transfer and the beginning of Shahed production some 500 miles east of Moscow in the Tatarstan region. Building thousands of Iranian Shaheds would allow Russia to address its shortages of drones and to manufacture precision munitions on the cheap.[20] This is an adaptation on the Kremlin's part. Previously, the Russian leadership was slow to recognize the added value of drone capabilities, so its military industrial complex did not have the capacity to mass produce these platforms in the required numbers.[21]

Ukraine, too, has developed long-range drones to strike airfields and logistics storage sites deep inside Russia. In the absence of other strike options with longer ranges, such as cruise missiles, these one-way attack drones fill an important capability gap. They also circumvent the restrictions on the use of long-range missiles donated by supportive Western governments. The first such attack occurred in June 2022, when Ukraine hit Rostov's oil refinery. Other notable attacks include distant targets such as Tu-22 bombers at Soltsy-2 Airbase in August 2023, and numerous assaults on the Kerch Bridge in Crimea. Attacks on fuel and ammunition depots in Luhansk have forced Russia to reposition its resources at considerable expense.

Ukraine has also adapted its drone production strategy. While the beginning of the war saw Kyiv repurpose commercially available, Chinese-built Mugin-5 drones ("Skyeye 5000"), Ukrainian forces later started building their own drone models for long-range strikes. For instance, the Ukrjet UJ-22 Airborne – one of the largest drones in service with the ability to carry 20kg of bombs at a range of 800km – attacked Moscow in February 2023. Other models include the UJ-25 Skyline (a weaponized version of the Ukrjet UJ-23 Topaz target drone) and the very distinctive UJ-26 Beaver (Bober) with a range exceeding 1,000km and 20kg of payload.[22]

Regional commands, elite special operations forces, and intelligence services operate a limited number of large MALE drones at higher altitudes. These roughly Cessna-sized aircraft can fly for 10 to 24 hours, conducting surveillance and intelligence gathering with high-resolution cameras. Drones of this size are most useful for strategic planning and precision strikes on high-value targets, since they can destroy tanks, artillery, naval vessels, logistics trains, and rocket launchers. However, their high cost makes their use less appealing due to their low survivability in contested airspace, as it is easy for the enemy to spot and destroy them. Large drones have thus almost disappeared from the battlefield except for shorter ISR flights.

1.2 Drone Weaknesses

Despite remarkable advantages, drone technology inevitably brings to the battlefield new weaknesses the adversary can exploit. This section cautions against five types of drone-related limitations.

First, thousands of small drones – with operators dispersed across different units – saturating the battlefield create a problem of deconfliction. Distinguishing one's own drones from the enemy's drones and conducting discriminate jamming can prove challenging.

Second, drones are vulnerable to weather conditions, such as high winds or heavy rain. Consumer electronics react poorly to cold temperatures that drain their batteries, meaning less airborne time. Similarly, during nighttime missions, drones require infrared and thermal night-vision cameras to operate. This can easily double the price of a drone and dilute its cost-effectiveness.

Third, drones have no self-defense capabilities, partly due to cheap manufacturing material and less-resilient consumer electronics. This can be exploited by the adversary in cyberspace. Two ways of doing this include hijacking drone software to access the data feed to locate enemy bases for strikes, and disabling the drone to make it easier for interceptors to destroy it. Some FPV drone exemplars have been fitted with counter-jamming devices as a result. But this add-on, like in the case of high-performance cameras, substantially increases the cost per drone and negatively affects their affordability.

Fourth, drones only give combatants a decisive advantage until the adversary finds an effective way to counter them. Drone warfare in Ukraine is exceptional in its fast adaptation cycles. The early, headline-grabbing drones were large, sophisticated Turkish Bayraktar TB2 drones on the Ukrainian side as well as Forpost and Orion military drones deployed by Russia. However, Russian troops soon learned how to down Ukraine's TB2s with electronic warfare (EW) measures. On the other side,

[20] Dalton Bennett and Mary Ilyushina, 2023, "Inside the Russian Effort to Build 6,000 Attack Drones with Iran's Help", The Washington Post, August 17, https://www.washingtonpost.com/investigations/2023/08/17/russia-iran-drone-shahed-alabuga

[21] Jeffrey A. Edmonds and Samuel Bendett, 2023, "Russia's Use of Uncrewed Systems in Ukraine", CNA Report, March, https://www.cna.org/reports/2023/03/Russian-Uncrewed-Systems-Ukraine.pdf

[22] H.I. Sutton, 2024, "Guide to Ukraine's Long Range Attack Drones", Covert Shores, June 24, http://www.hisutton.com/Ukraine-OWA-UAVs.html

analyzing one fallen Orlan-10 enabled the Ukrainians to develop a low-cost drone detector that could work against Russian military drones. Furthermore, the ubiquitous DJI Mavic drones turned into "a hazardous encumbrance" due to Russia's use of the AeroScope drone detection system.[23] Additionally, using new technology on the battlefield may eventually benefit the adversary's own drone program through reverse engineering,[24] given the high rates of drone attrition.

And fifth, drone outcomes do not occur in a vacuum. The success of a drone mission is highly dependent on the skills of its human operator and the technology supporting the drone, such as navigation and communication satellites.[25] FPV small racing drones are able to glide into trenches or through windows to kill individual soldiers only if they are in the hands of a skilled operator. After Russia's initial attack on Ukraine destroyed most communication networks, the American company SpaceX provided Ukrainian troops access to high-speed, space-based internet that also made drone operations possible. However, the company's CEO did not allow the Ukrainians to use its Starlink satellites for military purposes over Crimea.[26] Furthermore, due to resource constraints, neighboring Poland had to fund some 20,000 Starlink devices to help keep Ukraine's critical services running and connected to internet.[27]

To conclude, Chapter 1 examined the growing importance of drones on the battlefield. At the same time, its analysis challenged the notion of what constitutes a strategic advantage when it comes to technology. Not only are drones themselves getting cheaper and more accessible, but the operators' training is also decreasing in complexity and can be quickly applied to new models. However, instead of making simplified statements about drones revolutionizing battlefields, this chapter also highlighted five factors that can impede the success of drone missions. Scholars and policymakers should pay careful attention to such limitations when studying conflict dynamics.

2 Drone Technology Diffusion

Drones have been steadily proliferating to new actors and regions for over two decades. As a result, armed drone fleets are now part of the military arsenals of almost 40 countries. Yet, the war in Ukraine has intensified and diversified interest in weaponized drone technology around the globe.[28] Military commanders are taking note of drones providing real-time situational awareness, enhanced reconnaissance capabilities, and cost-effective munitions delivery.

The international drone market is thus expected to balloon to sales of more than 35 billion USD by 2028.[29] This is unsurprising given the attention garnered by the drones showcased on the battlefield in Ukraine and other recent conflicts in Syria, Libya, Nagorno Karabakh, and Israel and Gaza. The primary military drone producers remain China, Israel, Turkey, and the United States. However, new drone capabilities originating on the commercial market, with borderless internet improving their accessibility and ever-powerful consumer smartphones filling in as a command-and-control station, have made for unprecedented drone proliferation. Developments in enabling technology areas, such as infrared thermography and hyperspectral imaging, AI-enabled motion planning and computer vision, and high-power batteries, also contribute to this growth.[30] Chapter 2 therefore scans trends in the rapid evolution of drone technology. It discusses technological diffusion triggered by the war in Ukraine. The chapter's three sections are dedicated respectively to small and mid-sized drones, large-sized drones, and drone defenses.

23 Radio Free Europe, 2022, "Drone Wars: Ukraine's Homegrown Response to Deadly Chinese Detection Tech", July 14, https://www.rferl.org/a/drone-detection-war-ukraine-china-russia/31943191.html

24 David M. Allison, Stephen Herzog, Brendan Rittenhouse Green, and Austin Long, 2020 "Clandestine Capabilities and Technological Diffusion Risks", International Security 45(2), 194–198.

25 Antonio Calcara, Andrea Gilli, Mauro Gilli, Raffaele Marchetti, and Ivan Zaccagnini, 2022, "Why Drones Have Not Revolutionized War: The Enduring Hider-Finder Competition in Air Warfare", International Security 46(4), 130–171.

26 Joey Roulette, 2023, "SpaceX Curbed Ukraine's Use of Starlink Internet for Drones -Company President", Reuters, February 9, https://www.reuters.com/business/aerospace-defense/spacex-curbed-ukraines-use-starlink-internet-drones-company-president-2023-02-09

27 AFP, 2024, "Poland Funds 20,000 Starlink Devices to Support Ukraine's Military", Kyiv Post, May 7, https://www.kyivpost.com/post/32246

28 New America, 2024, "Who Has What: Countries with Armed Drones", https://www.newamerica.org/future-security/reports/world-drones/who-has-what-countries-with-armed-drones

29 Emergen Research, 2023, "Top 10 Globally Renowned Companies in the Military Drones Industry", April 21. https://www.emergenresearch.com/blog/top-10-globally-renowned-companies-in-the-military-drones-industry

30 Peter Bergen, Melissa Salyk-Virk, and David Sterman, 2023, "World of Drones", New America, July 30, https://www.newamerica.org/international-security/reports/world-drones

2.1 Small and Mid-sized Drones

This section highlights the growing attention to small reconnaissance and armed drones, including one-way attack drones and loitering munitions. Views of drones as game-changing wonder weapons notably contrast with past public opinion trends. Before Russia's war in Ukraine, many publics around the globe were largely resistant to the use of lethal drones, animated in part by visceral, but inaccurate, images of so-called killer robots.

Innovations in drone technology are already shaping military acquisition strategies globally. The most notable changes are occurring in the loitering munition category. Military-grade loitering munitions and commercial drones repurposed into (mostly one-way) attack drones have provided both Russia and Ukraine with the capability to strike troops on the frontline. Likewise, they present a threat to critical supply lines. They can perform both of these missions at a lower cost than other precision weapons. Consequently, even well-established drone powers lack certain capabilities when compared to forces that use small combat drones that can be fielded (and lost) in the thousands. Low unit prices make high-attrition strategies viable. Generally speaking, in the past decade, the use of loitering munitions and other types of disposable lethal drones was limited to special operation forces. This is now changing due to the war in Ukraine.

China, Israel, Turkey, and Russia already possess, or are developing, their own loitering munition capabilities. Additional countries acquiring this technology include Azerbaijan, India, and South Korea.[31] In the European region, significant growth in demand for loitering munitions is met by two major players: Germany's Rheinmetall producing the HERO series (together with Israeli UVision)[32] and Poland-based WB Group manufacturing the Warmate (with Georgia as its new local production site).[33] France's investment of 5 billion EUR into drones also includes a plan to develop French-made loitering munitions by 2030.[34] Furthermore, in Europe, interest in new types of both ISR and armed drones is growing. Drones are increasingly seen as the answer to a vastly changed strategic situation requiring new and adaptable capabilities. For instance, Sweden has moderate experience with operating American-made Shadow drones during the UN peacekeeping missions in Mali and Afghanistan, as well as Saab-made Skeldar V-200 reconnaissance drones. After the outbreak of Russia's full-scale war in Ukraine, Sweden has prioritized armed drones in its force adaptation.[35] On the whole, however, Western militaries are sitting on drone inventories designed for yesterday's drone warfare. The necessary force adaptation process will need to strike the right balance between investing in crewed aircraft, sophisticated drone platforms, and small disposable drones. Doing so will be imperative if militaries are to effectively integrate new drone capabilities into their existing forces.[36]

On the other side of the Atlantic Ocean, companies such as AeroVironment, Anduril Industries, and Teledyne FLIR are established leaders in the US loitering munition market. The Pentagon's new Replicator drone program aims to provide the US Armed Forces with a myriad of low-cost disposable drones, to enhance ground-based robotics, and to develop air defense systems to counter drones.[37] Ultimately, Replicator is designed to become one of the main mechanisms to harness and scale up commercial technology solutions for the military.[38] Similarly, since July 2023, the US Army has been working on the Low Altitude Stalking and Strike Ordnance, or LASSO, program. LASSO intends to provide soldier-portable, tube-launched, anti-tank loitering munitions to infantry brigades. These efforts are inspired by Washington's delivery of loitering munitions to Ukraine and their performance in combat.[39] US Army leadership even recognizes that fielding commercial drones to lower-level infantry combat teams would help them begin

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32 Rheinmetall, 2023, "Hungary Awards Rheinmetall and UVision a Major Contract for the Hero Loitering Munitions", Press Release, July 19, https://www.rheinmetall.com/en/media/news-watch/news/2023/7/2023-07-20-hungary-awards-rheinmetall-and-uvision-a-major-contract-for-the-hero-loitering-munitions

33 Derek Bisaccio, 2023, "Georgian-Polish Plant Launching Kamikaze UAV Production", Defense and Security Monitor, October 20, https://dsm.forecastinternational.com/2023/10/20/georgian-polish-plant-launching-kamikaze-uav-production

34 Rudy Ruitenberg, 2024, "France Rethinks Military Light-Drone Acquisition as Army Falls Behind", Defense News, June 18, https://www.defensenews.com/global/europe/2024/06/18/france-rethinks-military-light-drone-acquisition-as-army-falls-behind

35 SVT, 2023, "The Swedish Defense's Wish: Kamikaze Drones", April 9, https://www.svt.se/nyheter/inrikes/har-ar-dronarna-sveriges-forsvar-har-och-det-har-ar-de-som-vill-kopas-in; Valerie Insinna, 2022, "Drones, Sats and Rockets: As Sweden Looks to Boost Spending, It's Taking Lessons from Ukraine", Breaking Defense, December 19, https://breakingdefense.com/2022/12/drones-sats-and-rockets-as-sweden-looks-to-boost-spending-its-taking-lessons-from-ukraine

36 Dominika Kunertova, 2022, "The Ukraine Drone Effect on European Militaries", CSS Policy Perspectives 10(15), Center for Security Studies (CSS), ETH Zürich, https://css.ethz.ch/content/dam/ethz/special-interest/gess/cis/center-for-securities-studies/pdfs/PP10-15_2022-EN.pdf

37 US Department of Defense, 2024, "Deputy Secretary of Defense Hicks Announces First Tranche of Replicator Capabilities Focused on All Domain Attritable Autonomous Systems", May 6, https://www.defense.gov/News/Releases/Release/Article/3765644/deputy-secretary-of-defense-hicks-announces-first-tranche-of-replicator-capabil/

38 Noah Robertson, 2023, "Replicator: An Inside Look at the Pentagon's Ambitious Drone Program", Defense News, December 19, https://www.defensenews.com/pentagon/2023/12/19/replicator-an-inside-look-at-the-pentagons-ambitious-drone-program

39 Jon Harper, 2023, "Army May Procure Multiple Variants of LASSO Kamikaze Drones to Boost Production Capacity, Acquisition Chief Says", Defense Scoop, August 7, https://defensescoop.com/2023/08/07/army-may-procure-multiple-variants-of-lasso-kamikaze-drones-to-boost-production-capacity-acquisition-chief-says

experimenting with small drones, eventually filling the capability gaps quickly and frustrating enemy advances. Lastly, the US Marine Corps has launched the Organic Precision Fires-Light, a light loitering munitions program, to equip small units with a portable, armed loitering drone for rifle squads and platoons.[40]

2.2 Large-sized Drones

This section offers a reminder, that despite these tactical and technological advances, the appetite for large drones has not disappeared. The section accordingly maps the proliferation of the most popular models of this class of platforms. In Europe, Russia's invasion of Ukraine accelerated the completion of the Polish Air Forces airbase in Mirosławiec, now hosting a fleet of US MQ-9A Reaper drones. US Reapers have operated from Larissa Air Base in Greece and from the 71st Air Base at the Campia Turzii airfield in Romania to monitor the Black and Baltic Seas. The Polish base has proven critical to the implementation of ISR capabilities that are interoperable with NATO allies and allow the Alliance to patrol the Eastern front. Poland itself plans to buy new MQ-9B drones, and while waiting for their delivery, Warsaw has leased a fleet of MQ-9A Reapers from the US company General Atomics for 70 million USD.[41]

Large drones can pose problems, however. The harsh weather at the Mirosławiec Air Base in northern Poland at times prevents large drones from taking off. The Israeli company Elbit Systems delayed the delivery of six Hermes 900 HFE drones to the Swiss Armed Forces until the end of 2026 due to various technical issues with certification and de-icing. Only three of the six Israeli reconnaissance drones have been delivered to Switzerland since the purchase was first announced in 2015.[42]

Another issue lies in divergent strategic needs and industrial rivalries in the defense sector.[43] Despite several collaborative research and development projects involving a number of EU member states and institutions, an operational European drone is still not a reality. After almost two decades of concerted efforts by Airbus (Germany in the lead, with Spain), Dassault (France), and Leonardo (Italy), Eurodrone – a European equivalent of the American MQ-9 drone – is expected to take flight only by 2028. This means that most advanced drones currently operated by twelve European countries come from either the United States or Israel (except for Ukraine and Poland, which bought Turkish TB2 drones).

Yet, the comparative advantage of these large drones lies with their ability to perform ISR missions over vast areas. For instance, Denmark has ordered long-range drones to strengthen surveillance in the Arctic and the North Atlantic. With the close involvement of governments in the Faroe Islands and Greenland, this Arctic drone capacity package will include advanced radar sensors to monitor both civilian and military activities, contributing to Danish defense and security in the North Atlantic.[44]

Similarly, large drones are in high demand for maritime patrols in the Indo-Pacific region. The United States has sold 31 MQ-9B SkyGuardian drones for 4 billion USD to India as part of an initiative to advance its strategic technology cooperation in the region.[45] This will add to India's drone surveillance capabilities, already buoyed by its cooperation with Israel since 2018.[46] South Korea, too, has an emerging drone industry. Its Hanwha drones are expected to surveil the country's borders by 2028.[47] The Danish, Indian, and South Korean cases all show continued perceptions of large drone utility for national security, including for activities broadly associated with rising geopolitical competition.

Interestingly, the US Marine squadron known as "Phantoms" acquired MQ-9 Reapers in April 2023 to extend the reach and reconnaissance capabilities of its own drone program. This exemplifies a shift in focus towards coastal and border reconnaissance capabilities in the Indo-Pacific region.[48] Similarly, the British Royal Navy is testing its own ship-launched large Mojave drone platform, operated from onboard the HMS Prince of Wales, making it the first European maritime drone in its

40 Tedd South, 2024, "Marines Pick Three Companies for Loitering Munitions Program", Defense News, April 15, https://www.defensenews.com/news/your-marine-corps/2024/04/15/marines-pick-three-companies-for-loitering-munitions-program

41 Jaroslaw Adamowski, 2024, "Polish Defense Leaders Push 'Dronization' of the Armed Forces", Defense News, April 8, https://www.defensenews.com/global/europe/2024/04/08/polish-defense-leaders-push-dronization-of-the-armed-forces

42 Swissinfo, 2023, "Delivery of Israeli Drones to Switzerland Again Delayed", December 20, https://www.swissinfo.ch/eng/politics/delivery-of-israeli-drones-to-switzerland-again-delayed

43 Dominika Kunertova, 2021, "European Drone Clubs Stall Strategic Autonomy", CSS Policy Perspective 9(5), Center for Security Studies, ETH Zürich, https://css.ethz.ch/content/dam/ethz/special-interest/gess/cis/center-for-securities-studies/pdfs/PP9-5_2021-EN.pdf

44 Danish Ministry of Defence, 2024, "The First Partial Agreement Secures New Drones for the Arctic and the North Atlantic Region", January 18, https://www.fmn.dk/en/news/2024/the-first-partial-agreement-secures-new-drones-to-the-arc-tic-and-north-atlantic-region

45 Bryant Harris, 2024, "Biden Administration Moves Forward on India Drone Sale", Defense News, February 1, https://www.defensenews.com/unmanned/2024/02/01/biden-administration-moves-forward-on-india-drone-sale

46 NDTV News, 2024, "A First, India Delivers Made-In-Hyderabad Hermes Drones to Israel", February 9, https://www.ndtv.com/business-news/in-a-first-india-delivers-made-in-hyderabad-hermes-drones-to-israel-5024597

47 Gordon Arthur, 2024, "Korean Air Begins Producing Reconnaissance Drone for South's Military", Defense News, February 1, https://www.defensenews.com/unmanned/2024/02/01/korean-air-begins-producing-reconnaissance-drone-for-souths-military

48 Irene Loewenson, 2023, "Marine Corps Now Has Unit in Indo-Pacific Flying Reaper Drones", Marine Corps Times, August 3, https://www.marinecorpstimes.com/news/your-marine-corps/2023/08/03/marine-corps-now-has-unit-in-indo-pacific-flying-reaper-drones

category. However, Mojave is a version of the MQ-1C Gray Eagle produced by General Atomics and adapted for short take-off and landing.[49]

The popularity of Turkish drones also does not appear to be slowing. Since the 2000s, a political push for domestic production of drones within Turkey resulted in the international success of the Bayraktar TB2 drones by the defense company Baykar. This was quickly followed by other Turkish drones, such as Akinci HALE drones, and Anka-S propeller-powered drones produced by Turkish Aerospace Industries. In the span of only a few years, the proportion of indigenous drones used by the Turkish military rose from 20 to 70% by 2020.[50]

The headline-grabbing entrance of TB2 drones into the war in Ukraine further contributed to the commercial success of the platform. In 2019, only six TB2 drones were sold. By 2023, Turkey had exported over 500 TB2s to 32 countries. Notably, the TB2 commands a price six times lower than US Reaper drones. Consequently, Turkey's defense exports have risen by one billion USD since 2022 to 4.4 billion, largely thanks to drones and land systems.[51] Its latest version, the Bayraktar TB3 drone, is designed to be deployed from Turkey's own newly-developed drone carrier, the TCG Anadolu.

Elsewhere in the Middle East, Iran continues developing and improving its domestic drone capability. Its new Mohajer-10 has a range of 2,000km (built to reach Israel) and is said to position Iran as "an advanced and technological nation". However, the new long-endurance drones have yet to see combat and have their capabilities tested on the battlefield.[52] In addition, the new jet-powered Shahed model is thought to fly much faster and carry out strikes more effectively, bypassing ground-based air defenses because of its light weight.[53] Lastly, Karrar combat drones are said to be patrolling Iran's border areas after passing operational tests. They are armed with air-to-air missiles and have a range of 1,000km.[54]

The appeal of large drone platforms has also spread to a surprising place. North Korea has showcased two new drones that look like copies of the most famous American large drones, the RQ-4 Global Hawk and the MQ-9 Reaper. North Korea may have obtained the necessary design parameter information from Iran, which shot down one US Global Hawk drone in 2019. Known as Saetbyol-4 and Saetbyol-9, these drones demonstrate North Korean ambitions to increase its ISR capabilities. Yet, the performance of these systems, sensors, and satellite communication systems (and even engines) is likely inferior to what is advertised by the regime.[55]

2.3 Drone Defense

Over the past decade, repurposed small hobbyist drones have turned into an important asymmetric weapon with an ever-increasing presence in armed conflicts. Defending against these lethal airborne systems carries a specific set of challenges in terms of detection, tracking, identification, and the destruction of drone threats. However, the challenge of countering small, low-flying drones is not unique to Ukraine. This section therefore discusses the broader Western experience combating against small drones in the Middle East to better understand technical challenges in developing effective drone defenses.

To detect small drones, the defender can choose from a range of means, including radio frequency, radars, optical sensors, and acoustic systems. Once detected, the defender can stop the drone in two ways: soft-kill neutralization, such as electronic warfare; and hard-kill, or the physical destruction of the drone's ability to execute its mission by means of various interceptors.

However, detecting hostile small, low-flying drones is challenging for two main reasons. First, these consumer drones, fabricated from cheap materials such as cardboard, plastic, and plywood, have a low radar cross-section and can be mistaken for a bird and create false alarms. Only their battery packs, engines, and the carbon fiber frame make up their radar signatures. Inverse synthetic aperture radar could thus become a promising alternative for imaging and tracking drones, as it is able to capture drone size and geometric shape.[56]

Second, to avoid friendly fire on the frontline, drone detection systems need to distinguish enemy drones from friendly ones. With the airspace saturated by thousands of diverse drones, more recent systems now

49 Royal Navy, 2023, "Royal Navy's Successful Crewless Aircraft Trials Offer 'Glimpse into the Future' of Carrier Operations", November 17, https://www.royalnavy.mod.uk/news/2023/november/17/20231117-royal-navys-successful-crewless-aircraft-trials-offer-glimpse-into-the-future

50 The Undersecretariat for Defense Industries, 2018, "2018-2022 Savunma Sanayii Sektorel Strateji Dokumani" [2018-2022 Defense Industry Sector Strategy Document], Government of Türkiye, 50-53, https://www.ssb.gov.tr/Images/Uploads/MyContents/F_20180626095928654133.pdf

51 Burak Ege Bekdil, 2023, "Turkey's Defense and Aerospace Exports Grew Sharply in 2022", Defense News, July 17, https://www.defensenews.com/global/mideast-africa/2023/07/17/turkeys-defense-and-aerospace-exports-grew-sharply-in-2022

52 Associated Press, 2023, "Iran Unveils Armed Drone It Says Could Potentially Reach Israel", Voice of America News, August 22, https://www.voanews.com/a/iran-unveils-armed-drone-it-says-could-potentially-reach-israel/7235281.html

53 Abbie Cheeseman, 2023, "Watch: Iran Unveils New Deadly Jet-Powered Kamikaze Drone", The Telegraph, September 30, https://www.telegraph.co.uk/world-news/2023/09/30/shahed-drone-russia-ukraine-war-iranian-weapons

54 AFP, 2023, "Iran Unveils Drones Armed with Air-to-Air Missiles", Voice of America News, December 10, https://www.voanews.com/a/iran-unveils-drones-armed-with-air-to-air-missiles/7392132.html

55 Joseph Dempsey, 2023, "North Korea Plays An Imitation Game with New UAVs", IISS Military Balance Blog, August 18, https://www.iiss.org/en/online-analysis/military-balance/2023/08/north-korea-plays-an-imitation-game-with-new-uavs

56 Chenchen Jimmy Li and Hao Ling, 2016, "An Investigation on the Radar Signatures of Small Consumer Drones", IEEE Antennas and Wireless Propagation Letters 16, 649 –652.

use AI-enhanced analytics and classification systems that can process and analyze signals from various sensors (including radar, electro-optics, acoustics, and video analytic software) to search for drone threats while constantly updating the threat library of known drone profiles.

The most serious obstacle regarding drone interception is financial rather than technical, however. Effective drone defenses are very costly, and hobbyist drones are very affordable. This has led to the successful use of the exhaustion tactic in Ukraine. Russia frequently sends barrages of relatively cheap loitering munitions, some even as decoys without explosives, to deplete Ukraine's limited supplies of comparatively expensive air defense missiles to protect its cities and critical infrastructure. Ukrainian forces have been forced to adapt and are now reportedly also using firearms to stop attacking Russian drones.[57]

However, over the past decade, non-state actors in other conflict zones have gotten a hold of low-cost airpower assets. The first record of militants using explosive-laden hobbyist drones dates back to 2006, when Hezbollah attacked Israel from Lebanon.[58] Out of over 1,000 small drone attacks recorded between 2006 – 2023, more than 90% took place in the Middle East and North Africa. Commercially-driven improvements over this time period have included increased range, speed, payload capacity, and new control and coordination methods. These developments have occurred while still keeping the cost asymmetry in the militants' favor.[59]

In 2023, Yemen's Houthis intensified attacks on international shipping lanes in the Red Sea. Even though US Navy destroyers successfully shot down dozens of drones, the cost of defending against these attacks with existing means ultimately proved unsustainable.[60] To stop Houthi drones costing a few thousand dollars, the US Navy either uses a medium-range air defense Standard Missile-2 that costs 2.1 million USD per projectile, or a short-range Evolved Sea Sparrow Missile costing 1.8 million USD each. Ship guns represent a lower-cost option, albeit they are only viable at a very close range. This is problematic since the shorter the distance of the drone interception, the greater the risk of impact/costs of a failed interception.

In the pursuit of cost-effective ways to defend against the drone threat, militaries can use weapons of smaller calibers and at lower price-points than modern Western systems like NASAMS and Iris-T designed to intercept cruise missiles. These can include anti-aircraft machine guns, cannons, nests, or even drones. For instance, Anduril's Anvil-M counter-drone system defends against small drones by using a ground-launched drone that zips towards a target on a collision path like an autonomous kinetic interceptor. Another example is more indirect: The Eagle Eye synthetic aperture radar, in development by General Atomics for the US Army by 2026, is to be mounted on a Gray Eagle 25M drone that does target identification and tracking. It then communicates with another platform (a cannon or a directed energy weapon) to down the malign drone.[61]

Directed energy weapons are particularly promising as a better and more affordable solution to drone attacks.[62] These emergent weapons mainly come in two forms: waves and beams. While microwaves can overwhelm or fry electronic components at a distance, lasers punch holes through materials. For instance, Lockheed Martin is building a HELIOS layered laser defense system for the US Navy while the US Army has procured Leonidas by Epirus, which uses long-pulse, high-power microwaves to disrupt drones. Additionally, the US Air Force has invested in Tactical High-Power Operational Responder, or THOR, which is a high-powered microwave weapon designed to neutralize multiple drones.[63]

The most important advantage of directed energy weapons appears to be in countering saturation attacks. Targeting electronics could neutralize multiple drones in swarming formations at a fraction of the cost of the drone swarm. However, these countermeasures can only be deployed if there are sufficiently powerful energy sources within range of the drone attack.

Mastering EW to counter drones is Russia's specialty, as demonstrated against Turkish Bayraktar drones as early as the first months of the war. Since 2019, Russia has been running a counter-drone training program featuring EW measures and combining portable and wheeled systems such as Brisglebsk and Zhitel.[64] Russian forces have learned to integrate EW, missile systems, and

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57 Elisabeth Gosselin-Malo, 2024, "Ukrainian Forces Rig Machine Gun Networks to Down Russian Drones", Defense News, April 5, https://www.defensenews.com/global/europe/2024/04/05/ukrainian-forces-rig-machine-gun-networks-too-down-russian-drones

58 Håvard Haugstvedt, 2024, "Still Aiming at the Harder Targets: An Update on Violent Non-State Actors' Use of Armed UAVs", Perspectives on Terrorism 18(1), https://pt.icct.nl/article/still-aiming-harder-targets-update-violent-non-state-actors-use-armed-uavs

59 Thomas Pledger, 2021, "The Role of Drones in Future Terrorist Attacks", Association of the United States Army, https://www.ausa.org/sites/default/files/publications/LWP-137-The-Role-of-Drones-in-Future-Terrorist-Attacks_0.pdf

60 Lara Seligman and Matt Berg, 2023, "A $2M Missile Vs. A $2,000 Drone: Pentagon Worried Over Cost of Houthi Attacks", Politico, December 19, https://www.politico.com/news/2023/12/19/missile-drone-pentagon-houthi-attacks-iran-00132480

61 Stephen Losey, 2023, "General Atomics: New Radar to Turn Gray Eagles into Anti-Drone Hunters", Defense News, October 9, https://www.defensenews.com/air/2023/10/09/general-atomics-new-radar-to-turn-gray-eagles-into-anti-drone-hunters

62 Stuart Dee and James Black, 2024, "Directed Energy Dilemmas: Industrial Implications of a Military-Technological Revolution", RAND, February 20, https://www.rand.org/pubs/commentary/2024/02/directed-energy-dilemmas-industrial-implications-of.html

63 Colin Demarest, 2023, "Directed Energy Weapons Making Jump from Sci-Fi to Real World", C4ISRnet, September 18, https://www.c4isrnet.com/battlefield-tech/2023/09/18/directed-energy-weapons-making-jump-from-sci-fi-to-real-world

64 Samuel Bendett, 2021, "Russia's Real-World Experience Is Driving Counter-Drone Innovations", Defense News, May 23, https://www.defensenews.com/opinion/commentary/2021/05/23/russias-real-world-experience-is-driving-counter-drone-innovations

connected sensors to frustrate Ukraine's drone offensives. Russia's activities have not come without collateral damage. Its EW operations adversely affect non-combatants in places like the Black Sea region and impact commercial activities relying on GPS services.[65]

Electronic jammers, either mounted on the top of armored vehicles or fitted in soldiers' backpacks, have two main limitations. First, they need sufficient power; second, they can cover only a narrow range of the frequency spectrum.[66] This also means that the attacker can overcome the jammer-based defenses if each attacking drone is operating on a different frequency. While traditional physical defense against drones is losing to the offense, electronic jamming can also impair friendly drones operating on the same radio frequency.

Furthermore, non-kinetic means may get less effective, not only due to their limited range, but also due to increasing autonomy of drones thanks to AI and sensors. As the ability of drones to operate autonomously becomes the new normal, there will be no transmissions between the drone and its operator to jam or spoof.

However, Israel – the country with the most extensive experience countering drones – has learned to use a combination of technologies integrated into multi-layered air defense systems, such as the Iron Dome. The Rafael Advanced Defense Systems Drone Dome specifically detects drones through 360-degree radar, radio frequency sensors, and cameras. It then either jams the drone or stops it with lasers. Another Israeli company, Elbit Systems, manufactures the ReDrone system, which is mounted on vehicles for convoy protection against small drones. Lastly, the Drone Guard by Elta Systems uses hard-kill systems to protect mobile units. This includes the use of other drones to strike the hostile drone and a fire control system on a rifle that improves the accuracy of shots against drones.

More countries are following Israel's lead. For instance, the Netherlands has formed new air defense units that focus on short-range air defense, including a Stinger platoon and a counter-drone platoon.[67] Elbit Systems is also providing drone countermeasure systems to the Dutch Armed Forces to protect their air bases, naval ports, and critical non-military infrastructure. These drone defenses use electromagnetic signals to neutralize attacking drones under 20kg. The Swedish Armed Forces are also procuring drone countermeasure systems for mobile units, such as Danish-made Wingman and Pitbull for the detection and disruption of drones.

The Pentagon, too, is currently procuring several drone defense systems. The US Army's multitude of efforts to address drone threats include: a counter-drone training school,[68] new microwave weapons, a Stryker-mounted short-range air defense system with four Stinger missiles and autocannons, hand-held drone jamming systems by DroneBuster, and mobile systems against small, slow-flying drones.[69] Importantly, US military leadership is pursuing a layered approach to best protect its overseas bases.[70]

To conclude, Chapter 2 discussed the recent changes in drone capability development and drone diffusion dynamics across both small-to-mid-sized and large-sized drones. Its third section also demonstrated why conventional air defense systems fare poorly against saturation attacks by small-sized drones. Yet, it also noted that, despite the undeniably overwhelming comparative advantage favoring the offense, the effects of every weapon sooner or later get mitigated by a new countermeasure. However, the threat from drones is likely to increase due to rapid advancements in AI in the medium term.

3 Next Drone Breakthroughs

Chapter 3 offers a vision of drone capabilities for the next battlefields. It does so by exploring the three most promising developments in drone technology and tactics. First, drones have been slowly permeating all physical operational domains. Importantly, and in contrast to earlier models, both maritime and land platforms are now being deployed with lethal effect either as armed systems armed with explosives and missiles, or as loitering torpedoes. Second, while advanced sensors, jammers, and anti-jammers are shaping drone warfare dynamics in the short term, AI will be the main catalyst for technological breakthroughs in the long term – though the scope of its impact on the conduct of war is yet to be defined. Lastly, although drones will not replace crewed planes any time

65 Olga R. Chiriac and Thomas Withington, 2024, "Russian Electronic Warfare: From History to Modern Battlefield", Irregular Warfare Initiative, March 21, https://irregularwarfare.org/articles/russian-electronic-warfare-from-history-to-modern-battlefield

66 Paul Schwennesen, 2024, "Drones and Asymmetric Warfare in Ukraine and Israel", Geopolitical Intelligence Services, February 20, https://www.gisreportsonline.com/r/drones-ukraine-israel

67 Ministry of Defence, 2023, "New Air Defense Unit Specializes Against Drones and Aircraft", Government of the Netherlands, June 2, https://www.defense-aerospace.com/dutch-army-stands-up-new-air-defense-unit

68 Joe Saballa, 2023, "US Army Opens Drone Fighting School", The Defense Post, October 17, https://www.thedefensepost.com/2023/10/17/us-army-drone-school

69 Sam Skove, 2023, "US Army Scrambles to Catch Up to Rising Drone Threat", Defense One, October 6, https://www.defenseone.com/threats/2023/10/us-army-scrambles-catch-rising-drone-threat/391014

70 Sam Skove, 2023, "US Army Scrambles to Catch Up to Rising Drone Threat", Defense One, October 6, https://www.defenseone.com/threats/2023/10/us-army-scrambles-catch-rising-drone-threat/391014

soon, the new generation of air combat systems will compensate for human limitations with autonomous drones.

3.1 Full-spectrum Drone Warfare

This first section identifies recent advances in land and maritime (surface and underwater) uncrewed systems and examines their impact on the conduct of war. So far, ground robots have been less successful than their aerial and naval counterparts. Indeed, the arsenal of uncrewed systems operating in the maritime domain has proven highly effective, and the technology is diversifying rapidly.

Uncrewed Ground Systems

Both Russia and Ukraine have been using uncrewed ground vehicles (UGVs) on the battlefield. Russian UGVs, such as the Uran series, have been seen carrying supplies to frontline troops. Ukraine has tested more than 50 different UGV designs, mostly focused on drones that can transport injured soldiers from the battlefield. These tracked and wheeled ground robot prototypes can also make a difference performing dull, dirty, and dangerous tasks, such as mine laying and mine detection, reconnaissance, evacuations, and cargo delivery.

More UGV deployments are a consequence of the growing emphasis on ISR and lethal aerial drones that limit the movement of troops and increase the dangers of attacks on supply convoys and armored vehicles. UGVs, therefore, present an opportunity to gain an asymmetric advantage that does not increase human losses. They can gather intelligence (for example, the Russian "Pitbull" and "Partisan" robots); support rescue missions, including by playing a key role in providing medical care; and can also serve as remote weapon stations, carrying larger payloads than aerial drones and protecting garrisons (for example, the Russian "Sosna-N" anti-sniper system).

In addition to serving as robotic transport platforms, new UGV models are also charting their way into lethal missions. For instance, Russian ground drones are already equipped with grenade launchers. Ukrainian troops are operating UGVs equipped with a loitering ammunition launcher from the Estonia-based company MILREM Robotics. Known as THeMIS, the Estonian system has already become a staple among UGVs.[71] In addition to MILREM, companies leading UGV developments include Hyundai Rotem (HR-Sherpa), Rheinmetall (Mission Master), and Textron Systems (Ripsaw M-series). Other notable examples include the multi-purpose UGV Arion-SMET manufactured by Hanwha, a South Korean aerospace and robotics company. This system can be equipped with a remotely controlled machine gun.[72] Similarly, to improve the safety of combatants, US Marines have been testing "robotic goat" UGVs able to launch anti-tank rockets.[73] Russia has developed a loitering Buggy UGV ("kamikaze tank") that detonates by driving into its target.[74] China has revealed its robotic quadrupeds armed with a rifle for combat ops in urban environments.[75]

While it is difficult not to exaggerate the effects of these UGVs – as Ukrainian officials have dubbed them "the next game changer in this war"[76] – they are more challenging to build than aerial drones. This is simply because UGVs moving across the battlefield encounter a multitude of terrain obstacles, such as uneven surfaces, barbed wire, trenches, and/or ditches. This requires an advanced capacity for live information processing and repeated decision making. However, coupled with incomplete sensor input, compromised communication, and integration issues with other military units, the development and fielding of UGVs has been slow and their production and operation costs remain high.[77]

The current trend suggests that AI-enabled software and programming might help UGVs to execute their missions more autonomously to overcome obstacles. The ongoing debate about how to best move uncrewed ground capabilities forward therefore addresses the questions of desirability and the technical feasibility of autonomy for their effective performance. Crucially, there are arguments against maintaining a commander's control over vehicles with a growing capacity for independent action. These points pertain to efforts to avoid disrupting UGV performance at the expense of the mission. Finding answers to these questions is becoming

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71 Jaroslaw Adamowski, 2023, "Estonian Robotics Firm Offers New Variant to Help in Ukraine", Defense News, September 14, https://www.defensenews.com/digital-show-dailies/dsei/2023/09/14/estonian-robotics-firm-offers-new-variant-to-help-in-ukraine

72 European Defense Review, 2024, "Hanwha's Arion-SMET Successfully Completes Foreign Comparative Test with US Military", January 4, https://www.edrmagazine.eu/hanwhas-arion-smet-successfully-completes-foreign-comparative-test-with-us-military

73 Andrew Bray, 2023, "Marines Test Emerging Technologies at The Combat Center", US Marine Corps, October 19, https://www.marines.mil/News/News-Display/Article/3563689/marines-test-emerging-technologies-at-the-combat-center

74 Militarnyi, 2024, "Russia Produces Series of Ground FPV 'Kamikaze' Drones", June 3, https://mil.in.ua/en/news/russia-produces-series-of-ground-fpv-kamikaze-drones

75 Leo Shane III, 2024, "Chinese Military's Rifle-Toting Robot Dogs Raise Concerns in Congress" Defense News, June 19, https://www.defensenews.com/news/pentagon-congress/2024/06/19/chinese-militarys-rifle-toting-robot-dogs-raise-concerns-in-congress

76 Elisabeth Gosselin-Malo, 2024, "Ukrainian Officials See Ground Robots as 'Game Changer' in War", Defense News, March 14, https://www.defensenews.com/global/europe/2024/03/14/ukrainian-officials-see-ground-robots-as-game-changer-in-war

77 Amos Chapple, 2024, "Ground Drones: The Next Frontier of Unmanned Combat in Ukraine", Radio Free Europe, April 18, https://www.rferl.org/a/ground-drones-war-russia-invasion-ukraine/32911118.html

urgent as countries around the globe are developing lethal versions of ground robotic vehicles.

Uncrewed Maritime Systems

Maritime drones have traditionally been understood as aerial drones deployed from the deck of a navy vessel. Boeing Insitu's ScanEagle drone is a pioneer in the field. Designed in 2001 for commercial fishing, it soon became a valued asset in military maritime operations and one of the first drones mounted on a ship to support naval operations.[78] Together with rotary-wing platforms such as Schiebel's Camcopter S-100, the UMS Skeldar V-200, and Northrop Grumman's MQ-8 Fire Scout, maritime drones extend the vessel's sensor range in harsh and quickly changing weather conditions. Compared to helicopters, which are expensive and require enhanced maintenance given humid and saline conditions, rotary-wing drones help to reduce maintenance costs. The vertical take-off and landing (VTOL) mechanism allows drones to operate from naval vessels without launch or recovery infrastructure, providing them with greater tactical mobility. Maritime drones serve not only in ISR and search and rescue missions, but also perform logistics roles. For instance, the Boeing MQ-25 Stingray provides aerial refueling for the US Navy.

In Ukraine, naval drone capabilities – operating on the sea surface and under water – have already proven highly effective at countering the Russian invasion in the Black Sea region. Often overlooked and underestimated, Ukrainian drone boats deprived Russia's Navy of a safe base point. They successfully disrupted Russian naval freedom of operation in the Black Sea. While summer 2022 saw some prototype experiments, in autumn 2022, Ukraine attacked the Russian Navy stationed in the Sevastopol port using uncrewed surface and underwater systems. These strikes damaged warships, frigates, and minesweepers. Ukraine's surface drones are also supporting aerial attack drones in sinking Russian vessels and other slow-moving targets.[79] Improving the performance and range of maritime drones, such as small surface uncrewed powerboats and underwater loitering torpedoes, even enabled Ukraine to reach Crimea and Novorossiysk – an important Russian naval base and oil port in the eastern Black Sea.

The successes of maritime drones in Ukraine have inspired other countries to invest. Most of these efforts have focused on expanding the scale and impact of combat-capable uncrewed systems, designing drones for operations deployable from amphibious assault ships and aircraft carriers, and producing loitering munitions for ship-launched precision strikes. One of the most notable examples is the US Navy's Devil Ray drone boat, equipped with a Lethal Miniature Aerial Missile System.[80]

In addition to their ongoing weaponization, naval drones are also getting bigger, redefining drone classification charts. The maritime environment allows for the deployment of drones of unusual sizes, such as extra-large underwater drone submarines like Orca, developed by the US Navy.[81] This strategic maritime drone capability could deploy offensive weapons like torpedoes and mines that can remain at sea autonomously for months. The Orca uncrewed submarine is part of the US Navy's efforts to develop a more distributed fleet architecture that would spread maritime capabilities over an increased number of diverse platforms with low-cost impacts. Importantly, this would avoid concentrating resources on a relatively small number of high-value ships.[82]

Similarly, the US Defense Advanced Research Projects Agency, (DARPA) in collaboration with Northrop Grumman, is developing a massive, long-endurance Manta Ray underwater drone prototype. It is intended to carry payloads at low-power usage and require little maintenance.[83] Furthermore, these uncrewed underwater vehicles (UUVs) could be used as a combat weapon in naval warfare for attacking subsea cables transmitting data between continents. Likewise, they could conduct offensive naval mining operations.[84]

Russia is pushing the frontier in underwater drone technology. Its nuclear-powered underwater Poseidon drone, equipped with nuclear weapons, can allegedly devastate a coastal city and cause radioactive floods. However, it is likely to remain at the prototype stage and be used as a psychological weapon, serving mainly political, rather than military, objectives.[85]

Overall, maritime drones perform four main tasks. First, in the civilian sphere, high-resolution seabed and water column mapping is already showing remarkable developmental progress. The commercial use of

78 Dan Gettinger, 2014, "ScanEagle: A Small Drone Making a Big Impact", Center for The Study of The Drone at Bard College, https://dronecenter.bard.edu/scaneagle-drone

79 Wills, "Sea Drone Swarms".

80 US Naval Forces Central Command, 2023, "Exercise Digital Talon Advances Unmanned Lethality at Sea", Public Affairs, November 2, https://www.cusnc.navy.mil/Media/News/Display/Article/3576761/exercise-digital-talon-advances-unmanned-lethality-at-sea

81 Ronald O'Rourke, 2023, "Navy Large Unmanned Surface and Undersea Vehicles: Background and Issues for Congress", Congressional Research Service, Report R45757, August 24, https://sgp.fas.org/crs/weapons/R45757.pdf

82 Aaron-Mathew Lariosa, 2023, "Navy Receives First of Six Prototype Extra Large Orca Underwater Drones", USNI News, December 21, https://news.usni.org/2023/12/21/navy-receives-first-of-six-prototype-extra-large-orca-underwater-drones

83 Colin Demarest, 2024, "Northrop's Colossal Manta Ray Underwater Drone Passes At-Sea Tests", Defense News, May 2, https://www.defensenews.com/unmanned/2024/05/02/northrops-colossal-manta-ray-underwater-drone-passes-at-sea-tests

84 Scott Savitz, 2023, "Could Taiwan Defend with Uncrewed Surface Vessels?", RAND, Commentary, January 9, https://www.rand.org/pubs/commentary/2023/01/could-taiwan-defend-with-uncrewed-surface-vessels.html

85 Silky Kaur, 2023, "One Nuclear-Armed Poseidon Torpedo Could Decimate A Coastal City. Russia Wants 30 of Them", Bulletin of the Atomic Scientists, June 14, https://thebulletin.org/2023/06/one-nuclear-armed-poseidon-torpedo-could-decimate-a-coastal-city-russia-wants-30-of-them

underwater drones for sea exploration includes the Hugin 6000 drone underwater system, by US-based Deep Sea Vision, that may have found the remains of Amelia Earhart's plane that vanished in 1937.[86] In terms of maritime security, underwater drones help survey natural gas pipelines (like Nord Stream 1 and 2 in the Baltic Sea following a September 2022 explosion), the seabed, and harbors.[87] Uncrewed surface vessels represent yet another potential venue. The German Sonobot 5 catamaran, equipped with a sonar system, can support hydrographic surveying of obstacles and foreign objects, which is valuable intelligence for improving military mobility.[88]

Second, UUVs have great potential as mine countermeasures. Machines like the battery-powered REMUS-series, manufactured by L3Harris Technologies, launches from and is then recovered by a tube. In the future, this technology could be used to collect acoustic signatures for anti-submarine warfare.[89]

Third, uncrewed surface vehicles can provide harbor security by protecting ships from terrorist attacks. They may do so using electro-optical cameras, loudspeakers, and a remote-controlled machine gun.[90]

Finally, uncrewed vessels can improve deception capabilities in anti-submarine warfare. For instance, Russia's Surrogate underwater drone is designed to deceive potential adversaries by reproducing signals from other submarines.[91]

Yet, underwater communication and networking remains a challenging and underdeveloped area for maritime drones. This is particularly due to the long distances common in the maritime environment. Thus, space-based satellite guidance and resilient communication have proven to be a must for executing naval drone strikes. While underwater drones may be harder to detect and intercept than their aerial counterparts, they are vulnerable when resurfacing to use their electro-optical cameras. Other persistent problems concern cost, the acoustic signal emitted by the propellor, and overall maneuverability.[92] However, developing autonomy at sea is just one of the ways to leverage new technologies for advanced maritime capability.

3.2 AI-enabled Drone Warfare

Rapid technological breakthroughs in AI are leading to new levels of algorithmic warfare – the integration of advanced algorithms into military operations to secure strategic and tactical advantages.[93] This third section thus looks at the different roles of military AI and the varying success rates of current AI-powered systems.

Military AI in Decision Making

In Ukraine, AI is already assisting decision makers to act and better integrate warfighting systems on the battlefield. Ukraine has relied on various foreign AI tech companies for data analytics. In fact, AI's most widespread use in the Ukraine war is in geospatial intelligence for object recognition. AI is used to analyze satellite images, but also to geolocate and sort through open-source data such as social media photos in geopolitically sensitive locations. For instance, facial recognition technology like Clearview has detected the identity of invading Russian troops and Ukrainian collaborators. Natural language processing software like Primer has aided in real-time analysis of Russian unencrypted radio transmissions. And Scale AI has processed vast amounts of imagery of Ukraine.

Most remarkably, the Ukrainian Armed Forces use digital battle management software that facilitates and accelerates the integration of various data collection points and formats – such as photos, videos, and imagery. This leads to the production of intelligence reports based on pattern identification. Delta app on the operational level, and GIS Arta on the tactical level, create real-time battlefield maps that are crucial for tracking the war's developments, like the movement of Russian troops. These programs are also useful for sharing target coordinates.

Military AI in Targeting

Drones with AI capabilities better connect and integrate into battle management systems and can operationalize AI-generated insights more effectively. Indeed, thanks to AI data analytics, the time from detection of a target to its destruction has, in some cases, been reduced to just over

86 Associated Press, 2024, "Has Amelia Earhart Mystery Been Solved? Underwater Drone Captures Grainy Image", Euronews, January 31, https://www.euronews.com/next/2024/01/31/has-the-amelia-earhart-mystery-been-solved-underwater-drone-captures-grainy-image-of-aircr

87 Megan Eckstein, 2023, "US Navy Tests Sub-Launched Drones While Industry Continues Designing", Defense News, November 8, https://www.defensenews.com/naval/2023/11/08/us-navy-tests-sub-launched-drones-while-industry-continues-designing

88 Bundeswehr, 2024, "Overwater Drone for Minden Pioneers", January 17, https://www.defense-aerospace.com/german-bridging-troops-deploy-new-sonar-drone

89 Joseph Trevithick, 2023, "Navy Submarine Just Tested a Torpedo Tube-Recovered Drone", The Drive, December 11, https://www.twz.com/navy-submarine-just-tested-a-torpedo-tube-recovered-drone

90 Kyle Mizokami, 2020, "The U.S. Navy's New Robo-Boat Has No People, But It Does Have a Very Big Gun", Popular Mechanics, February 19, https://www.popularmechanics.com/military/research/a31003656/cusv-robot-drone

91 H.I. Sutton, 2022, "Russia Reveals Radical New Stealth Missile Submarine", Naval News, August 16, https://www.navalnews.com/naval-news/2022/08/russia-reveals-radical-new-stealth-missile-submarine

92 Tom Kington, 2024, "Italian Government Halts Plan to Buy Israeli Undersea Drones", Defense News, April 10, https://www.defensenews.com/global/europe/2024/04/10/italian-government-halts-plan-to-buy-israeli-undersea-drones

93 Martin Klein, 2024, "Decoding the Battlefield: The Power of Algorithmic Warfare", ECS, February 14, https://ecstech.com/ecs-insight/article/decoding-the-battlefield-the-power-of-algorithmic-warfare

30 seconds. However, accelerated targeting and strike cycles with decision-making processes powered by AI are likely to come with inherent biases for speed and action. This may come to pose a significant problem since AI accelerates the battlefield that is still very much human-centric.

Publicly available evidence points to the use of autonomous, sensor-based targeting that includes autonomous object recognition and terminal guidance. This usually applies in cases of radio interference and jamming that prevent the direct operator's control. Following the rise of drone countermeasures based on EW systems, which disrupt drones' communication, navigation, and data links, drone tech developers have been experimenting with a greater level of autonomy and integration of AI systems. Object recognition already features in the American-made Switchblade 300, as well as terminal guidance in the Russian FVP drone Ovod.[94] Even though loitering munitions are not known for their advanced specs or accuracy,[95] the internal inertial navigation in micro-electromechanical systems could be sufficient over short ranges and make loitering munitions immune to jamming.

Quite remarkably, Ukraine's new Saker Scout drones, trained on machine learning, are able to independently identify 64 different types of Russian targets while also carrying explosives.[96] Furthermore, this FPV drone can automatically lock onto and then fly into its target, even under conditions of intense radio jamming. While Ukrainian drone manufacturers claim to keep the human operator in the loop, they cannot ensure drone strike accuracy due to, for instance, an underspecified target or a system malfunction.

Some analysts suggest that drones do not use more autonomy than standard missiles able to conduct autonomous terminal guidance. This means that drones are finding potential targets and relaying that information to the human operator, who in turn confirms legitimate targets or approves of the area in which those targets are likely to exist. Drones then lock on the target and execute the mission, with no role for AI to play in the actual decisions. Others disagree with this assessment, as AI-generated insights based on automated data analytics can accelerate the targeting process. For instance, the Israeli AI system Lavender uses machine learning to sift through data to find targets for airstrikes. [97]

Drone-to-drone Coordination

So far, instead of relying on fully autonomous targeting processes, ISR and FPV drones are working in tandem. The reconnaissance drone identifies targets and passes the information to a human-operated FPV attack drone, which then strikes the target. AI could significantly expand the scope of drone usage by managing large numbers of robotic systems simultaneously. The Ukrainian company Swarmer has already tested a primitive form of swarm, in which AI-powered command software allows a single technician to operate multiple ISR and suicide drones.[98] However, machine-to-machine teaming requires a machine language so that drones can talk to each other, and the human operator must learn this drone communication.[99] To date, at least eleven states have invested in drone swarm projects.[100]

Recent advances in AI promise machine-to-machine teaming among drones of different sizes, operational domains, and functions. Swarming provides the potential for AI to yield a tangible battlefield advantage. Expensive, high-quality platforms could become vulnerable to low-cost weapon platforms networked together in the form of AI command and control, such as quadcopters, FPV drones, and small fixed-wing UAVs. Experimenting with multi-domain swarms involves an intelligence collecting drone coordinating with a UGV to perform reconnaissance.[101] For instance, Elistair and Rheinmetall Canada are working on pairing Khronos surveillance drones and eight-wheeled Mission Master SP robots to follow troops and deliver packages of weapons and sensors. Similarly, Singapore-based ST Engineering is developing a UGV equipped with a multi-rotor drone called Taurus.[102] However, without self-defenses, the adversary can target the navigating drone to blind the UGV or target the vehicle by merely spotting its navigating drone in the sky.

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94 The Economist, 2024, "How Cheap Drones Are Transforming Warfare in Ukraine", February 5, https://www.economist.com/interactive/science-and-technology/2024/02/05/cheap-racing-drones-offer-precision-warfare-at-scale

95 Ingvild Bode and Tom Watts, 2023, "Loitering Munitions and Unpredictability", AutoNorms, University of Southern Denmark, https://www.autonorms.eu/loitering-munitions-and-unpredictability-autonomy-in-weapon-systems-and-challenges-to-human-control

96 David Hambling, 2023, "Ukraine's AI Drones Seek and Attack Russian Forces Without Human Oversight", Forbes, October 17, https://www.forbes.com/sites/davidhambling/2023/10/17/ukraines-ai-drones-seek-and-attack-russian-forces-without-human-oversight

97 Yuval Abraham, 2024, "'Lavender': The AI Machine Directing Israel's Bombing Spree in Gaza", +972 Magazine, April 3, https://www.972mag.com/lavender-ai-israeli-army-gaza

98 Paul Mozur and Adam Satariano, 2024, "A.I. Begins Ushering in an Age of Killer Robots", New York Times, July 2, https://www.nytimes.com/2024/07/02/technology/ukraine-war-ai-weapons.html

99 Thomas Fox-Brewster, 2023, "Do You Speak Droidish? The Pentagon Is Spending Millions on a Language for Drones", Forbes, September 18, https://www.forbes.com/sites/thomasbrewster/2023/09/18/droidish-ai-drone-swarms-pentagon

100 Zachary Kallenborn, 2024, "Swarm Clouds on The Horizon? Exploring The Future of Drone Swarm Proliferation", Modern War Institute, March 20, https://mwi.westpoint.edu/swarm-clouds-on-the-horizon-exploring-the-future-of-drone-swarm-proliferation

101 Colin Demarest, 2024, "Rheinmetall Canada, Elistair Pair Robots and Drones in Test for Europe", C4ISRNet, January 17, https://www.c4isrnet.com/unmanned/2024/01/17/rheinmetall-canada-elistair-pair-robots-and-drones-in-test-for-europe

102 Elisabeth Gosselin-Malo, 2024, "ST Engineering Unveils Wheeled Ground Robot Equipped with Aerial Drone", Defense News, February 21, https://www.defensenews.com/unmanned/2024/02/21/st-engineering-unveils-wheeled-ground-robot-equipped-with-aerial-drone

Another example of machine-to-machine teaming uses a mothership model to pair drones of different sizes. The large Gray Eagle drone is involved in testing a new family of air-launched, low-cost, multi-purpose drones called EAGLET (Enhanced Air and Ground Launch Effect Technology).[103] Combining the high altitude and long-range sensors of a Gray Eagle with the lethality of small EAGLETs operating at lower altitudes within the danger zone represents a new generation of advanced machine-to-machine teaming in terms of command and control.

Persistent Limitations

Looking ahead, rather fundamental problems lie with the use of AI on the battlefield. AI is expected to help avoid information overload by enhancing the speed and quality of data analysis. AI-enabled data processing systems are thought to sift through the information noise of the large amounts of data now instantly available from the battlefield. However, AI algorithms can be fooled through decoys and concealment, or misled by rogue data that can lead to classification inaccuracies.

Although some analysts claim that autonomous weapons are just one software update away from revolutionizing warfare, the reality might be more complex.[104] Military AI systems, to become reliable, need iterated testing and evaluation. Although Russia is taking military AI seriously[105] – creating its own dedicated AI weapons department in August 2022 – it remains to be seen how effective this investment will be. Due to the sanctions on Russia, major advancements in AI-enabled weapons are improbable, as evidenced by the failures of the prematurely fielded – and allegedly "fully autonomous" – version of the Lancet drone.[106] Undeterred by such failures, however, Russia shortened the testing and evaluation of its AI-powered one-way attack drones to a matter of weeks. Indeed, experimentation with military AI on active battlefields only exacerbates the ongoing technological race.

Ultimately, military AI systems have object recognition, not situational awareness. While the nature of war means the battlefield cannot be defined by stable patterns of behavior or information, the machine learning present in most AI-enabled military systems relies on probabilistic logic and trains on controlled data sets. No amount of data or computing power can correct this mismatch between AI model architecture and often uncertain elements in war (yet). In contrast to assumptions about rapid robot wars, AI-enabled conflicts will still require human qualities, like intuition and judgment, to make decisions.[107]

3.3 Human-machine Teaming

Now, this section turns to mapping the urgent challenges posed by the exponential rise of human–machine interactions. Importantly, effective human–machine teaming will be a crucial component in building the strategic technological advantage of any modern military. While machine–machine teaming relies on well-programmed software, human–machine teaming requires well-designed interfaces.

The EU considers human–machine teaming one of the key technologies to watch out to 2035.[108] Indeed, the ongoing European multinational project, Future Combat Air System, will team crewed New Generation Fighters with a drone of a high – but unspecified – level of autonomy. It aims to do so while connecting all systems through cloud architecture by 2040.[109]

China, the largest producer and exporter of drones and their components, already includes human–machine teaming as a standard part of military training. Chinese leadership considers advances in AI and autonomy central to drone modernization efforts across all operational domains and drones crucial to its pursuit of "intelligentized warfare".[110]

The United States, too, is intensifying the research and development of autonomous features in drones to enable effective human–machine teaming. Several projects explore the concept of autonomous collaborative platforms, such as the Kratos XQ-58 Valkyrie that supports F-22 and F-35 fighters, Boeing's MQ-28 Ghost

103 Emma Helfrich, 2023, "MQ-1C Has Air-Launched the Eaglet Drone On Its First Flight", The Warzone, February 1, https://www.twz.com/mq-1c-has-air-launched-the-eaglet-drone-on-its-first-flight

104 Paul Sharre, 2024, "The Perilous Coming Age of AI Warfare", Foreign Affairs, February 29, https://www.foreignaffairs.com/ukraine/perilous-coming-age-ai-warfare

105 Anna Nadibaidze, 2022, "Great Power Identity in Russia's Position on Autonomous Weapons Systems", Contemporary Security Policy 43(3), 407–435.

106 Sydney J. Freedberg Jr, 2024, "The Revolution That Wasn't: How AI Drones Have Fizzled in Ukraine (So Far)", Breaking Defense, February 20, https://breakingdefense.com/2024/02/the-revolution-that-wasnt-how-ai-drones-have-fizzled-in-ukraine-so-far

107 Avi Goldfarb and Jon R. Lindsay, 2021, "Prediction and Judgment: Why Artificial Intelligence Increases the Importance of Humans in War", International Security 46(3), 7–50.

108 Marta Kepe, James Black, Jack Melling, Jess Plumridge, 2018, "Exploring Europe's capability Requirements for 2035 and Beyond", RAND Europe and European Defence Agency, https://eda.europa.eu/docs/default-source/brochures/cdp-brochure---exploring-europe-s-capability-requirements-for-2035-and-beyond.pdf

109 Stefanie Pfingsten, 2024, "The FCAS Future Combat Air System Nations Will Strengthen Their Partnership During Pacific Skies", Bundeswehr, April 16, https://www.bundeswehr.de/en/the-fcas-nations-are-consolidating-their-cooperation-5765642

110 US Department of Defense, 2023, Military and Security Developments Involving the People's Republic of China. A Report to Congress, 49, 97, 169, https://media.defense.gov/2023/Oct/19/2003323409/-1/-1/1/2023-MILITARY-AND-SECURITY-DEVELOPMENTS-INVOLVING-THE-PEOPLES-REPUBLIC-OF-CHINA.PDF

Bat, Anduril's Fury, and General Atomics' Gambit.[111] However, the current cost estimates for these loyal wingmen are still remarkably high – between 20–27 million USD per drone – when considered in reference to the intended "will fight, can lose" logic of modern drone warfare.

International context notwithstanding, the integration of human force with robots has also been driven by rapid development of commercial technology. Most notably: The computational power of AI models is growing and becoming more refined; sensors are lighter and smaller; connectivity solutions are diverse and resilient; and space-based capabilities are available as never before.[112]

However, for human–machine teaming to achieve its desired effect, the integration of drones into human force structures needs to address two major challenges. The first one concerns the relationship between the cost of the drone, still very high at present, and the military's risk acceptance and tolerance for drone losses in combat. The second challenge extends far beyond drones: finding the correct balance between the level of the machine's autonomy, effective mission performance, and meaningful human control. In this case, autonomy does not apply to the complexity of the machine, but rather, to the human–machine relationship in terms of command and control.[113]

Ideally, the parameters for meaningful human control over a machine's speed of data processing and decision making should be tested in stressful simulated situations and under time pressure. Advances in augmented-reality command and control systems could enable a major step towards functional and user-friendly human–machine interfaces. However, some analysts argue that effective interfaces would require enhanced human cognition, through human augmentation, to allow for meaningful human control over AI-powered weapon systems.[114] Discussion of the arguments for, and against, this point is beyond the scope of this report.

To summarize, Chapter 3 outlined the current technology-driven innovations in drone deployments in order to anticipate what future drone warfare may look like on the battlefield (see Table 2). The future of autonomous weapon systems will depend on advances in machine learning methods, coupled with progress in the

Table 2: Next Drone Breakthroughs

Trend	Promise	Problem
Full-spectrum Drone Warfare	Lethal drone systems will spread across the air, land, and maritime operational domains, enabled by the increasingly important space and cyber domains.	• Overcoming physical obstacles specific to the air, land, and maritime domains • Keeping the price tag low • Slow progress in autonomous navigation at sea and AI-powered UGV's decision making
AI-enabled Drone Warfare	Technological breakthroughs in AI will improve autonomous drone capabilities and elevate algorithmic warfare to new levels.	• Military AI has object recognition, not situational awareness and intuition • AI's near real-time data processing ability is biased towards speed and action
Human–drone Team Warfare	The new generation of air combat systems will rely on the collaboration of piloted aircraft with autonomous drones to enhance airpower and overcome human limitations.	• Defining the human fighter's risk acceptance and tolerance for combat hardware loss • Striking the balance in the complex relationship between the level of a machine's autonomy, the team's effective mission performance, and the human's meaningful control

111 Stephen Losey, 2024, "Here Are the Two Companies Creating Drone Wingmen for the US Air Force", Defense News, April 24, https://www.defensenews.com/unmanned/2024/04/24/here-are-the-two-companies-creating-drone-wingmen-for-the-us-air-force

112 Jen Judson, 2024, "The Robots Are Coming: US Army Experiments With Human-Machine Warfare", Defense News, March 25, https://www.defensenews.com/unmanned/2024/03/25/the-robots-are-coming-us-army-experiments-with-human-machine-warfare

113 Paul Scharre and Michael C. Horowitz, 2015, "Introduction to Autonomy in Weapon Systems", Center for a New American Security Working Paper, February, https://s3.us-east-1.amazonaws.com/files.cnas.org/hero/documents/Ethical-Autonomy-Working-Paper_021015_v02.pdf

114 Katrine Nørgaard and Michael Linden-Vørnle, 2021, "Cyborgs, Neuroweapons, and Network Command", Scandinavian Journal of Military Studies 4(1), 94–107.

areas of sensors and robotics. Yet, for most new drone systems, their successful fielding will require overcoming physical obstacles specific to the air, land, and maritime domains while simultaneously keeping their price tag low.

4 Policy Implications

This research report has examined major drone developments on the battlefield in Ukraine, outlined the resultant constants and changes in drone diffusion and procurement strategies, and pointed to technology-driven trends in drone deployments. Building on these insights, Chapter 4 discusses the policy side of future uncrewed capabilities along three main themes: the innovation adoption challenge, ethical and legal concerns, and export control regimes.

4.1 Innovation Adoption Challenge

Embracing drone diversity along with a whole range of new enabling technologies poses a three-fold innovation challenge. This section outlines upstream adoption in terms of organization (supply chains and procurement) and people (human skills/capital), as well as downstream adoption in terms of force integration and doctrine.

Military organizations are known to struggle to cope with technological changes. This is true both in terms of research and development, as well as long-duration procurements with rigid parameters for budgetary oversight. To best harness the advantages of small and inexpensive drone technology, national governments need to devise more responsive procurement processes that would hit three benchmarks.

First, the speed of procurement needs to increase to match pace with technological development and evolving threats. This means allowing militaries to experiment with new equipment and change it in line with the needs of soldiers, all without having to obtain additional funding under new programs.

Second, national procurement agencies need to reach out to new suppliers, recognizing that most tech innovation happens in the private sector. This means collaborating closely with vetted, non-traditional companies from the tech sector under flexible contracts that would allow for commercial solutions to capability gaps. For instance, NATO has already made Alliance-wide steps to create a transatlantic defense start-up ecosystem to modernize the its approach to technology-driven capability development.[115]

Third, since recent drone innovations have led to massive reductions in the cost-per-effect ratio, the procurement process needs to deliver systems with an appropriate unit cost and quantity.[116] Adopting different drone models at the same time can also create issues with safety standards and interoperability, alongside problems with scaling new commercial technology solutions.[117]

Several national initiatives are already testing out new approaches to the innovation adoption challenge. The Pentagon's Replicator initiative checks the boxes of engaging new partners, keeping the cost of drones low, and scaling up commercial solutions. France, too, is changing its acquisition process for small drones. Similarly, the United Kingdom's new drone strategy prioritizes innovation and industry partnerships. London aims to scale up technologies developed in the commercial sector.[118]

However, the robotization of armed forces and integration of AI-powered systems does not eliminate the burden of maintaining human capabilities. It is the relentless human-driven adaptability to an opponent's countermeasures that helps to prevail in conflict. Most new emerging technologies, especially the uncrewed ones, require people with new skills and roles. This also remains true in the case of autonomous drones, so long as the requirement for meaningful human control remains desirable.

The adaptation of land forces should reflect two key developments brought about by the widespread use of drones. First, the proliferation of surveillance drones armed with sensors has introduced an unprecedented level of transparency onto the battlefield. The force adaptation process therefore needs to include updating and improving deception and dispersal tactics. Second, in terms of defending against drones, minimal signatures and low costs of small drones challenge the organization of air defense for mobile units and the protection of troop bases. The combination of the continuing

115 Dominika Kunertova and Stephen Herzog, 2024, "NATO and Emerging Technologies: The Alliance's Shifting Approach to Military Innovation", Naval War College Review.

116 Zach Rosenberg and Meredith Roaten, 2023, "US Army Seeking Tube-Launched, Anti-Armour UAVs", Janes, July 24, https://www.janes.com/defence-news/news-detail/us-army-seeking-tube-launched-anti-armour-uavs

117 Seth G. Jones, Riley McCabe, and Alexander Palmer, 2023, "Ukrainian Innovation in a War of Attrition", CSIS, February 27, https://www.csis.org/analysis/ukrainian-innovation-war-attrition

118 Ministry of Defence, 2024, "Defence Drone Strategy the UK's Approach to Defence Uncrewed Systems", United Kingdom, February 22, https://assets.publishing.service.gov.uk/media/65d724022197b201e57fa708/Defence_Drone_Strategy_-_the_UK_s_approach_to_Defence_Uncrewed_Systems.pdf

proliferation of low-cost drones in lower airspace with the limited number of air defense systems requires a reorganization of the existing division of labor between specialized air defense units and other force units.[119]

4.2 Ethical and Legal Concerns

During past counterterrorism operations, the use of drones was challenged on ethical and legal grounds because of the dubious use of force outside declared war zones. Some critical voices called drone strikes assassinations, pointing to controversial "signature strikes".[120] In contrast, as this section portrays, the ethical concerns in contemporary drone warfare are related to the technology itself: increasing levels of autonomy and human ability to exercise command and control over these systems.

The recently popularized narrative that AI and autonomy can provide the best defense against electronic jamming has only increased experiments with military AI in Ukraine. However, experts are largely divided when it comes to the impact of AI on the battlefield. AI defenders see the advantage of such systems in reducing casualties by both improving accuracy and removing soldiers from the frontlines. Furthermore, AI's near real-time data processing ability is believed to help humans with decision making. However, AI skeptics are concerned about passing targeting decisions to an algorithm that is biased towards speed and action alongside the risk of rogue data making AI systems unreliable. Ultimately, the strategic advantage of AI-enabled autonomous systems is yet to be demonstrated in comprehensive comparative case studies from the lab or the battlefield.

What is worrisome, though, is that computer scientists have argued that the capability of lethal autonomous machines is easier to develop than that of a self-driving car. Both state and non-state actors can equip commercial drone tech with AI-powered software to create a low-cost smart weapon. From a technical perspective, therefore, meaningful human control is possible only when there is "no communication between the on-board computing and the firing circuit … [so that] the firing has to be activated by a remote operator and cannot ever be activated by the AI". [121]

Global governance of military AI is struggling to keep pace with the fervor of states and arms companies caught up in an AI gold rush. This has led to legal ambiguity regarding emerging AI-powered autonomy.[122] Most attempts at regulating lethal autonomous weapons have been hindered by clumsy definitions made by policymakers with little technical background. The UN Group of Governmental Experts (GGE), the main international initiative examining AI-enabled weapons in light of international humanitarian law, has been formally tasked since 2013 to develop regulations for lethal autonomous systems that do not exist yet. Furthermore, the GGE requires consensus for its decisions, and some of its members have an interest in actively developing such weapons to gain strategic advantages. Importantly, the general setting matters, too. The GGE operates within the UN Convention on Certain Conventional Weapons, a 1983 treaty that addresses specific weapon systems. However, AI and autonomy are features that are capability-agnostic. Autonomy itself is not a weapon. These sorts of dilemmas and the dual-use nature of the technology make any sort of regulation,[123] let along arms control, a very complicated proposition.

To speed up the efforts at regulating military AI in lethal systems, in October 2023, the UN General Assembly voted for a new resolution expressing concerns about the negative impact of autonomous weapons on international security. The resolution urged the international community to address the diminishing role of humans in the use of force.[124] The UN Secretary General even expressed the wish to ban weapons that operate without human oversight by 2026 and to regulate all other types of autonomous weapons systems.[125] For the reasons noted above, this appears to be a long-distance run, not a sprint.

In contrast, three notable international and national initiatives aimed at regulating the use of military AI emphasize voluntary guidelines rather than legally enforceable limitations or bans. First, the Dutch- and South Korean-sponsored international summit on the responsible use of AI in the military domain took place in February

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119 Shaan Shaikh, Tom Karako, Michelle McLoughlin, 2023, "Countering Small Uncrewed Aerial Systems: Air Defense by and for the Joint Forces", CSIS, Missile Defense Project Report, November 14, https://www.csis.org/analysis/countering-small-uncrewed-aerial-systems

120 Target selection was determined by behavioral patterns rather than the individual's identity. See Lucy Suchman, 2020, "Algorithmic Warfare and the Reinvention of Accuracy", Critical Studies on Security 8(2), 175–87; Lauren Wilcox, 2015, "Drone Warfare and the Making of Bodies out of Place", Critical Studies on Security 3(1), 127–31.

121 David Adam, 2024, "Lethal AI Weapons Are Here: How Can We Control Them?", Nature, April 23, https://www.nature.com/articles/d41586-024-01029-0

122 Dominika Kunertova, 2023, "Autonomous Weapons: Technology Defies Regulation", CSS Analyses in Security Policy 320, Center for Security Studies (CSS), ETH Zürich, https://css.ethz.ch/en/center/CSS-news/2023/03/autonomous-weapons-technology-defies-regulation.html

123 Jane Vaynman and Tristan A. Volpe, 2023, "Dual Use Deception: How Technology Shapes Cooperation in International Relations", International Organization 77(3), 599–632.

124 United Nations General Assembly, 2023, "Lethal Autonomous Weapons Systems", Resolution A/C.1/78/L.56, October 12, https://documents.un.org/doc/undoc/ltd/n23/302/66/pdf/n2330266.pdf

125 United Nations, 2013, "A New Agenda for Peace", Policy Brief 9, July, https://www.un.org/sites/un2.un.org/files/our-common-agenda-policy-brief-new-agenda-for-peace-en.pdf

2023. The summit presented itself as a forum for multi-stakeholder and depoliticized dialogue. It set in motion knowledge building and the sharing of best practices to shape the normative framework for global governance of military AI. Second, in October 2023, the United States issued a political declaration that encouraged measures to ensure the responsible development, deployment, and use of military AI capabilities. The US declaration has since been endorsed by more than 50 other countries.[126] Third, the 2021 NATO AI strategy has committed the Alliance and its members to ensure that their military applications of AI will follow six principles of responsible use.[127]

While the EU adopted its own Artificial Intelligence Act in May 2024, it only covers the areas within EU law and thus cannot apply to military AI systems. The Act, however, allows the EU to set standards in the civilian domain, which may affect their military use.[128]

Overall, a formal, legally-binding international treaty to ban a vaguely understood category of new weapons does not appear to be in the cards in the short- to medium-term. Emerging technologies like AI require a novel approach to control their applications and capabilities, not the technology itself. Near-term risk mitigation measures that enhance transparency, reduce risks of misperception, and set user standards are more achievable, actionable, and impactful. These may include crisis communications systems, shared definitions, unilateral declarations, and confidence-building measures.[129] Such initiatives may produce the sorts of mutual understanding that help to open doors for more expansive regulation and arms control in the future.

4.3 Export Control Regimes

Several factors facilitate the spread of drone technology to hostile actors across the globe. These include technical expertise circulating on the internet (including for 3D-printing/additive manufacturing), insufficient customs checks at porous national borders, under-resourced sanction enforcement mechanisms, online shops operating internationally, and access to unsecured explosives. This section points out that, while those factors are immensely difficult to address systematically, the underlying cause – commercial availability – is not.

Most drone technology comes from private sector companies that develop their products for commercial markets. Consumer drones and their components are then repurposed and weaponized for military missions. This cycle makes military drone transfers and developments of concern difficult to detect and curtail due to insufficient export control mechanisms. In contrast to military-grade drone systems usually addressed through the framework of the Arms Trade Treaty (ATT) and the Missile Technology Control Regime (MTCR), the Second (and Third) Drone Age necessitates a new approach to regulatory regimes.

For instance, over 90% of computer chips and electrical components used in Russian drones imported from Iran are manufactured in the West, mostly in the United States. Iran's attack drones also contain several components made in European countries.[130] Specifically, Shahed-136 drones are powered by a copy of the German Limbach Flugmotoren L550E engine, use a transistor made by a subsidiary of the German firm Infineon Technologies AG, have a fuel pump manufactured in Poland, and rely on a microcontroller with built-in flash memory made by the Swiss firm STMicroelectronics. Similarly, the Shahed-131 model also contains a microprocessor made by the Dutch company NXP Semiconductor and a GPS tracker chip made by the Swiss firm U-blox.[131]

Yet, these are all commercial electronic components that were not designed for military use in drones. Nor were they designated as sensitive technology and thus subject to export control prior to Russia's invasion of Ukraine.[132] However, even if a company had strict internal policies, once exported these goods are freely available. Furthermore, secondary and tertiary sales are difficult to monitor. For instance, sanction-laden Iran still continues to import commercial drone technology through third countries. New supply-side controls might well make a difference.

Multilateral export controls and a global trade compliance program are needed to regulate the spread of drone technology and monitor the implementation and

126 US Department of State, 2023, "Political Declaration on Responsible Military Use of Artificial Intelligence and Autonomy", Bureau of Arms Control, Deterrence, and Stability, November 9, https://www.state.gov/political-declaration-on-responsible-military-use-of-artificial-intelligence-and-autonomy-2

127 NATO, 2021, "Summary of the NATO Artificial Intelligence Strategy", October 22, https://www.nato.int/cps/en/natohq/official_texts_187617.htm

128 Council of the European Union, 2024, "Artificial Intelligence (AI) Act: Council Gives Final Green Light to The First Worldwide Rules on AI", Press Release, May 21, https://www.consilium.europa.eu/en/press/press-releases/2024/05/21/artificial-intelligence-ai-act-council-gives-final-green-light-to-the-first-worldwide-rules-on-ai

129 Shannon Bugos, 2023, "Arms Control Tomorrow: Strategies to Mitigate the Risks of New and Emerging Technologies", Arms Control Association, May 1, https://www.armscontrol.org/sites/default/files/files/Reports/ACA_Report_ArmsControlTomorrow_0.pdf

130 Daniel Boffey, 2023, "Revealed: Europe's Role in The Making of Russia Killer Drones", The Guardian, September 27, https://www.theguardian.com/world/2023/sep/27/revealed-europes-role-in-the-making-of-russia-killer-drones

131 Conflict Armament Research, 2023, "Documenting the Domestic Russian Variant of the Shahed UAV", Ukraine Field Dispatch, August, https://storymaps.arcgis.com/stories/d3be20c31acd4112b0aecece5b2a283c

132 Bennett and Ilyushina, "Inside the Russian Effort to Build 6,000 Attack Drones with Iran's Help".

enforcement of rules. Such regulatory regimes would set the standards for authorizing the use of sensitive products and facilitate better coordination among national intelligence services to address their unauthorized use.

Innovating export control of drones – and related enabling technologies – with the intention of limiting their proliferation means making acquisition lengthier and costlier. This pertains to the technology, components, and systems. Export control rules that raise the cost of drones and complicate supply chains will slow the spread of technology and deprive the adversary of asymmetric advantage.

Export control rules therefore require two adjustments. First, state agencies partnering with private actors need to incentivize the latter to co-develop effective regulatory regimes with functioning compliance verification mechanisms. Second, while the hardware–software challenge creates a verification conundrum, shifting the focus away from the platform to include service provision may open further paths for effective export control through software modifications, updates, and the geographical limitation of connectivity.

Conclusion

Over the past few years, drones have gotten cheap, commercial, and ubiquitous. Small-sized drones have increased airborne diversity on the battlefield, and their wide availability has enabled life-saving battlefield innovations. This has led many observers to note that drones have "changed the rules of the game", especially in terms of affordability. From providing real-time video transmission capabilities to becoming disposable ammunition, drones not only acquire and destroy their targets but can also disrupt enemy tactics and exhaust air defenses. Undoubtedly, drones utilizing new technologies are transforming warfare.[133]

However, this report parts ways with popular claims about drones "revolutionizing" warfare. Such sensational statements do nothing but admit a grim situation in which Ukraine does not have much choice but to innovate from cheap consumer drones. Calling contemporary drone warfare a "Drone Revolution in Military Affairs" is therefore myopic.[134] In the end, victory on the battlefield never depends solely on cutting-edge technology. The compound effects of investing in human skills, building resilient navigation and communication networks, and working around enemy countermeasures should not be underestimated.

Looking ahead, future drone wars will feature uncrewed systems across the air, land, and sea domains. They will be won by those who master complex algorithmic warfare, incorporating digital technologies and AI-powered systems into an interconnected data architecture. Keeping the cost of drone countermeasures lower than technologically inferior, but inexpensive, attack drones will be equally important. While AI and advanced robotics cannot replace humans, technology can team with humans. Autonomous drones will become integral to future warfare as long as human–machine teaming satisfies the parameters of meaningful human control without compromising combat effectiveness.

Finally, the international community remains largely unprepared for the prospects of the upcoming Third Drone Age. Adopting innovative technological solutions still poses immense organizational and bureaucratic challenges. Many unanswered ethical and legal questions surround the development and testing of military AI. In addition, most new drone technology originates in the private sector. Yet, adapting export control rules to dual-use realities still lags far behind drone innovation.

133 Jack Watling, 2023, The Arms of the Future: Technology and Close Combat in the Twenty-First Century (New Perspectives on Defence and Security), Bloomsbury Academic; Clint Hinote and Mick Ryan, 2024, Empowering the Edge: Uncrewed Systems and the Transformation of U.S. Warfighting Capacity, Special Competitive Studies Project, https://www.scsp.ai/wp-content/uploads/2024/02/SCSP-Drone-Paper-Hinote-Ryan.pdf

134 Bradley Perrett, 2024, "Small, Cheap and Numerous: A Military Revolution Is upon Us", The Strategist, Australian Strategic Policy Institute, January 22, https://www.aspistrategist.org.au/small-cheap-and-numerous-a-military-revolution-is-upon-us

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