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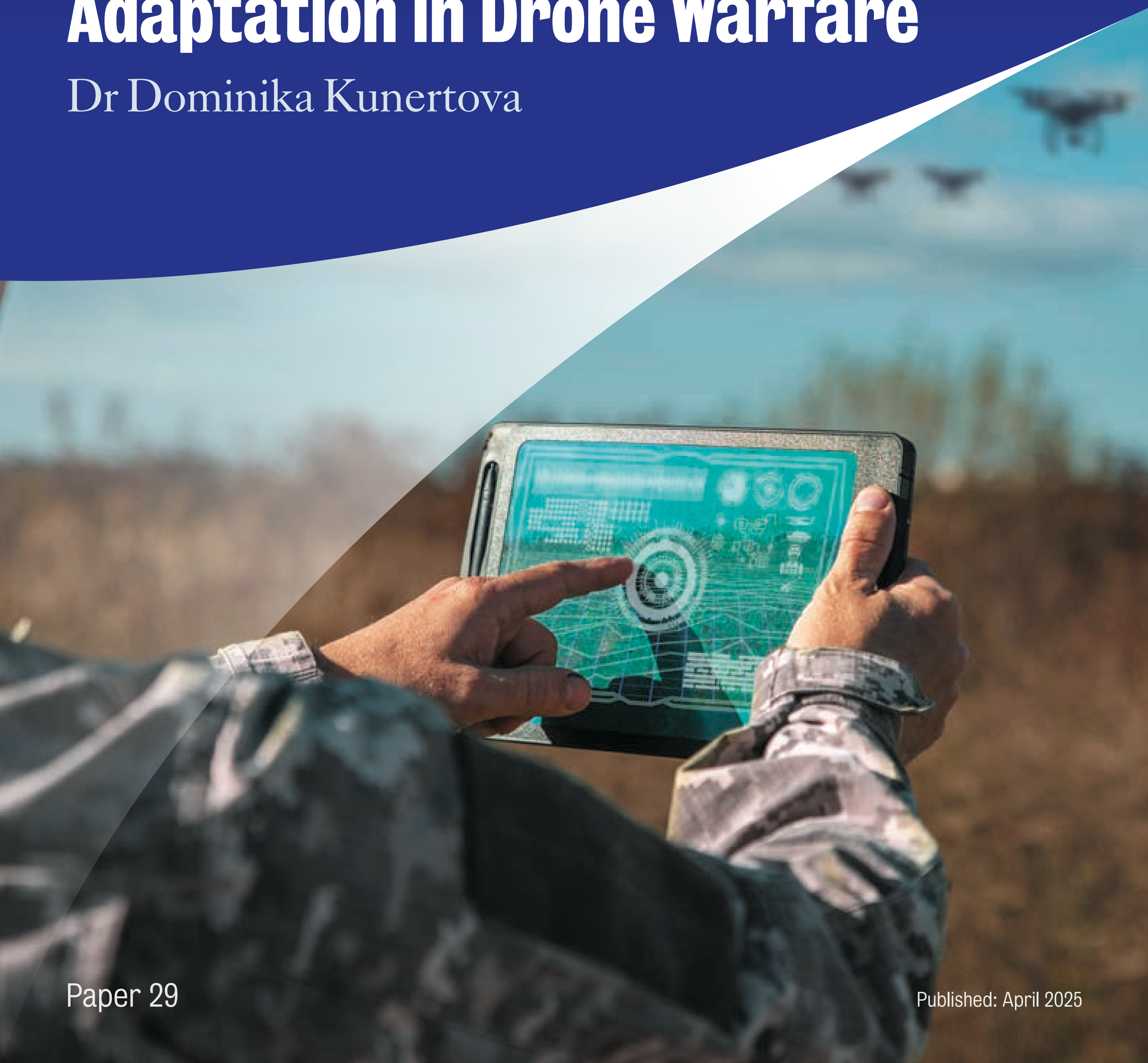

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About the Author

Dr Dominika Kunertova is an independent research scientist specialising in military applications of emerging technologies, international security, and transatlantic defence cooperation. A former NATO international staffer, Dr Kunertova recently served as a Senior Researcher at ETH Zurich, where she worked on uncrewed systems in the context of Russia's war in Ukraine. Her ongoing research on drone warfare, autonomy, and artificial intelligence received grant awards from the NATO Science for Peace and Security and NATO Chief Scientist programmes. She has published her academic research and public affairs commentary in the Bulletin of the Atomic Scientists, Contemporary Security Policy, Defence Studies, the Naval War College Review, RUSI Newsbrief, and more. Dr Kunertova is also a non-resident senior fellow at the Atlantic Council and an affiliate researcher at the Peace Research Center Prague. She holds a PhD in Political Science from Université de Montréal.

Abstract

Contemporary drone warfare highlights key implications for doctrinal and force structure adaptation. Lessons from the Russia-Ukraine war have led Western policymakers and defence planners to make modest organisational changes to enhance the drone capabilities of their armed forces. There is a growing demand for intelligence from surveillance drones, a surge in loitering munitions procurement, and new approaches to defence innovation. Yet, military doctrines have lagged in adapting to the rapidly evolving drone landscape. The West still lacks small armed drone equivalents and diversified countermeasures.

Western militaries face five main challenges: procurement practices, public-private partnerships, drone safety, drone defence, and AI-enabled autonomy. Integrating new drone capabilities requires new suppliers. The emergence of new defence technology firms demands innovation in both strategies and means to leverage civilian advancements. The emphasis on procuring drones "cheap, fast, and many" has shifted focus toward cost-effective hardware quantity and updatable software quality. While digital tools and AI are advancing rapidly, current drone operations show limited military use of AI on the battlefield. The changing character of drone warfare reflects a broader trend of structural change. The rapid incorporation of commercial technologies into military operations has increased mass availability while reducing warfare costs.

Introduction

Drone diversity has become a defining feature of contemporary warfare. Small and inexpensive drones in unprecedented numbers are impacting the battle rhythm with improved battlespace awareness and low-cost munition delivery. Their tactical impact has transformed the battlefield, prompting militaries to reconsider the role of uncrewed systems in terms of platforms and functions. Indeed, Russia's ongoing war on Ukraine reveals that exponential developments in drone technology and operations are changing the character of warfare.

This paper examines these emerging drone dynamics and anticipates their impact on Western militaries. The core argument is simple but challenging in practice: Instead of investing limited resources into a few exquisite uncrewed platforms, embracing drone diversity will become necessary to leverage comparative advantages in intelligence and munition.

> Embracing drone diversity will become necessary to leverage comparative advantages in intelligence and munition

Militaries are now facing the complex task of adjusting their drone procurement strategies and adapting their force structures and doctrines. The process of reinventing airpower and transforming air forces has already begun.[1] Transitioning from a single costly platform to thousands of small, affordable drones – amid the growing threat they pose – will necessitate a strategic division of labour among armed services. This shift will be challenging.

Western armed forces have largely operated without dedicated small drone units, lacking an equivalent to small armed drones. However, lessons from the Russia-Ukraine war are reshaping this stance, softening past reluctance, and shifting perceptions of armed drones. This change is already evident in the rising demand for surveillance drones, increased procurement of loitering munitions, and new approaches to defence innovation. Yet, this may only mark the beginning of next-generation drone warfare. This paper identifies **five challenges** for Western military adaptation as they embark on drone diversity:

1. **Procurement:** New drone capabilities will require faster, cheaper, and larger-scale acquisition – three benchmarks that are difficult to achieve simultaneously.
2. **Integration:** New defence tech providers and resilient enabling commercial technologies will be essential for successfully integrating drones into military operations.
3. **Operations:** Troops must mitigate the vulnerabilities of new drones while keeping costs low.
4. **Air Defences:** Intensifying drone threats requires leveraging new technologies to close air defence capability gaps and better coordination between army air defence units and air forces.
5. **AI and Autonomy:** Experimentation with AI-powered drones is progressing, but effective integration requires clearly defined operational roles for autonomous systems. Autonomous target identification, navigation, and command – enhanced by digital infrastructure – only approximate the future of autonomous drone wingmen.

While addressing these technology-driven challenges, military leaders must not forget to invest in human capital. This paper concludes with remarks on the unique value of human skills and innovative spirit. Managing expectations about new drone capabilities may be the most challenging task for policymakers and defence planners as they brainstorm how to adapt armed forces for future warfare.

Changing Character of Drone Warfare

This century, drone warfare has largely relied on large airborne platforms like the American MQ-1 Predator and MQ-9 Reaper, primarily targeting international terrorism across the Middle East and Sub-Saharan Africa. These advanced, long-endurance drones – valued for their remote operation, powerful sensors, and missile capabilities – have sparked debate over the legitimacy of precision warfare.[2]

Modern drone warfare has evolved – it is less remote and less reliant on high-end technology.[3] The shift began with the rising export of military drones such as China's Wing Loong and Turkey's Bayraktar TB2. These affordable yet lethal platforms have played more than a fleeting role in conflicts across Syria and Libya, while several African nations now deploy drones against local insurgencies. The Bayraktar TB2, in particular, gained prominence during the 2020 Nagorno-Karabakh War, where it enabled Azeri forces to destroy Armenian tanks and armoured vehicles and overwhelm Armenian air defences.

Furthermore, non-state actors have taken advantage of easily accessible and inexpensive hobbyist drones and drone parts.[4] The offensive use of drones has never been a prerogative of state actors. Across the globe, various militias, crime organisations, and terrorist groups have used small, makeshift drones for reconnaissance, propaganda, smuggling, and flying improvised explosive devices (IEDs) to attack foreign bases.[5] Far from representing advanced air assets for strategic ends, these drones have caused asymmetric damage relative to their cost. For example, Hamas deployed inexpensive drones to drop munitions on tanks and one-way attack drones for targeted strikes during its October 2023 attack on Israel.[6]

> "The offensive use of drones has never been a prerogative of state actors

The Houthis – one of the most drone-active militant groups – have demonstrated their capability to damage targets inside Yemen and Saudi Arabia. The most notable examples were in 2019, when they attacked a military parade in Aden and Saudi Aramco oil facilities. The Houthis use copies or variants of Iran-made drones, built with inexpensive commercial parts, to target multi-million-dollar assets in the Red Sea and Gulf of Aden.

Interestingly, the Afghanistan-Pakistan region highlights the limitations of small drones. The Taliban deployed them against the conventionally superior Afghan National Defence Security Forces but disbanded their drone unit after regaining power in 2021. This may reflect a status shift – drones are tools of asymmetric warfare, more suited to insurgents than governments. However, practical factors likely play a greater role, including the region's rural, open terrain and the continued availability of cheaper alternatives such as IEDs and suicide bombers.[7]

Over the past few years, consumer drones have mutated from a security nuisance into combat assets. The spread of increasingly cheap drone technology across borders and types of actors has altered cost and risk calculations on the battlefield and challenged existing air defence.[8] Recent conflicts have seen uncrewed systems operating in increasingly physically and electronically contested environments. This has been most evident in Russia's war on Ukraine after 24 February 2022.

Drones of the Ukrainian Battlefield

The war in Ukraine is the first full-scale war between two modern armed forces featuring drones deployed in unprecedented numbers and types by both sides. Most strikingly, small drones have greater potential than just threatening military bases; they have become offensive assets for air warfare in lower airspace. Commercially available and blurring military and civilian components, low-cost hobbyist drone technology is changing the rules of warfare.[9]

This war has already seen significant tactical successes achieved using diverse types of drones, filling gaps in expensive traditional weaponry. Contrary to the operational rationale for drone deployments in past wars, drones in Ukraine provide battlespace awareness to ground units and enable human-guided ammunition delivery. Two other novel aspects of drone warfare in Ukraine include drone use for psychological effects and the digitised, AI-enabled operational environment. While the initial use of drones led to changes in brigade composition by incorporating drone assault units, the establishment of Unmanned Systems Forces is now driving distinct structural reforms in Ukraine.

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Drones in Ukraine provide battlespace awareness to ground units and enable human-guided ammunition delivery

Since the Russian full-scale invasion of Ukraine, the war has shown progressive technological adaptation and tactical innovation in drone combat by both sides. Initially, Turkish-made TB2 drones halted Russian convoys but soon became cost-ineffective due to their size, making them easy targets in contested airspace. Consequently, their use was limited to short ISR (Intelligence, Surveillance, Reconnaissance) missions, while small drones provided close support. Ground troops have increasingly relied on consumer drones to scout, drop grenades in guerrilla-style warfare, and provide situational awareness *en masse*, highlighting the importance of repurposed, low-cost drones.

Recent conflicts have seen a rise in explosive anti-personnel and anti-armour drones, operating like missiles by hovering over target areas before striking. Azerbaijan used the Israeli Harop drone against Armenian forces in 2021, while in Ukraine, Russia deployed its domestically developed Lancet series by ZALA. Meanwhile, Ukraine received US-made Switchblade drones from AeroVironment and Polish Warmate drones. More infamously, Russia has frequently launched barrages of relatively inexpensive Shahed-136 loitering munitions, produced by Iran's Shahed Aviation Industries, to exhaust Ukraine's limited stock of far costlier air defence missiles used to protect cities and critical infrastructure.

First-person-view (FPV) drones represent the next step in improving small drone operations and tactics. FPV drones are a homemade version of loitering munition assembled from crowdfunded commercial components that cost less than 500 USD (in contrast to typically thousands for military-grade loitering munition). They are small and cheap, just like the low-tech, grenade-dropping consumer quadcopters. FPV drones, however, are designed for speed and manoeuvrability. Originally conceived as racing drones, FPV drones in Ukraine are equipped with improvised warheads and strike mobile targets like tanks and light-armour vehicles.[10]

Since they can be operated beyond sight, FPV drones are a go-to weapon for precision strikes behind buildings and dive-bombing in trenches.[11] FPV drone attacks can be more effective and easier to execute than calling an airstrike. The favourable cost-effect ratio and effective trade-offs between range, payload, and navigability even led some to suggest FPV drones could replace artillery. FPV drones are cheaper than a mortar round (a basic US Army mortar costs around 600 USD) and more accurate than artillery.[12]

The drone versus artillery debate demonstrates an important point. Drones do not achieve effects in a vacuum. They convey the most powerful results in terms of fire correction, when they improve the precision of artillery and thus reduce the number of artillery shells that miss their target. In other instances, FPV drones coordinate with an ISR drone.[13] Such coordination can reduce the targeting cycle of artillery fire from detection to destruction to just a few minutes.

Drones are thus deployed in a growing variety of missions. ISR tasks have traditionally been the main occupation of drones. Drones, equipped with live streams and data collection sensors, can provide battlefield transparency, assist in assessing battle damage, and facilitate war crime documentation. Weaponised small drones can drop bombs, hand grenades, and anti-tank mines or become ammunition themselves as one-way attack drones. However, in Ukraine, the distinction between armed and unarmed drones has become less clear in terms of lethal effects. ISR drones enable target identification and support strike operations with other weapons.

Drone warfare can also have significant psychological effects. For example, drones can spread propaganda and amplify disinformation by sharing livestream videos of ambushes on social media. More directly, drones can intimidate adversarial forces by hovering over the battlefield to detect soldiers on the run.[14] Due to acoustic effects, drones can approximate a sonic weapon that can confuse and distract soldiers, causing discomfort and mental health effects. Reports show soldiers surrendering to a drone dovetail with the 'paralytic' dread of hearing a buzzing sound in the air.[15] In addition, an airborne drone can signal that an adversary's artillery is close. As Ukraine improved its long-range drone capabilities, its makeshift one-way-attack drones began to make their way deep inside Russian territory to make ordinary Russians in Bryansk, Kursk, and Moscow aware of the war. These drones also destroy targets with strategic significance, such as airfields and logistics storage facilities.

> "The war in Ukraine has accelerated the extensive use of digital tools and experimentation with AI for military purposes

The war in Ukraine has accelerated the extensive use of digital tools and experimentation with AI for military purposes. Ukraine's government has encouraged private tech companies to pitch their products to the military while building a drone innovation ecosystem around Kyiv. Diverse battlefield management apps and onboard data analytics for target identification have sped up Ukraine's drone operations. The Delta platform enhances situational awareness, while Bronya and GISArta systems support artillery fire, and Kropyva aids in planning. All rely on intelligence data collected by the AI-enhanced Griselda system, creating an interconnected data architecture that accelerates the sensor-to-shooter cycle.[16]

Furthermore, autonomous navigation is expected to be an antidote to electronic warfare (EW) that increases both hit rates and survivability of drones on a jammed battlefield. Since September 2023, the Ukrainian government has encouraged projects imbuing its 'Army of Drones' with AI-enhanced navigation, autonomous task performance, and target identification. The war has, therefore, turned into a test bed for foreign tech companies that defy most regulatory assumptions about responsible development.[17]

While both sides are engaged in an intense drone war, Ukraine's efforts most visibly drive technological innovation and inspire tactical adaptation. Drones can sometimes partially compensate for weaker firepower but cannot fully replace long-range precision missiles. The offence-defence competition fuels rapid innovation-adaptation cycles, exemplified by drone warfare.[18]

Three tactical developments stand out:

1. Drones enable forces to occupy rather than control airspace, overwhelming enemy defences by offensive saturation with waves of small sensors, decoys, and bombs, making operational advantage nearly impossible.
2. Drones are integrated into both positional warfare and manoeuvres, for instance, with Ukraine using a combination of drones and jammers to enter Russian territory.
3. Russia uses loitering munitions not just to destroy targets but also to expose, disrupt and exhaust Ukrainian defences.

Regarding force structure, Ukraine's new Unmanned Systems Force will be dedicated to drone warfare in addition to extant specialised drone assault and reconnaissance units across army brigades, the National Guard, and national security and military intelligence services. This new drone branch reflects a culmination of the integration of drones into regular armed forces unseen in modern militaries.[19] However, it might be difficult for military organisations to adapt and absorb new technology and concepts that change the operational level of warfare.[20] Yet, incremental advances in low-end drone tech have proven crucial for the active tactical use of drones in Ukraine. Futuristic swarms have not.[21]

Western Militaries Rethink Drones

Since Russia's full-scale invasion of Ukraine, three noticeable changes have shaped the West's attention to drones. First, lethal drones are no longer seen as 'taboo.' Small drones and loitering munitions are now valued tactical assets rather than just safety concerns. Second, drone intelligence has heightened the appeal of a transparent battlefield. Finally, many countries are pursuing initiatives to adopt commercial drone technology, bypassing traditional supply chains.

Lethal Drones

The war in Ukraine has shifted the military's perception of small drones, leading to greater acceptance of lethal drones overall.[22] Previous drone deployments in counterterrorism operations sparked campaigns against governments equipping uncrewed systems with missiles. Human rights activists questioned the legitimacy of using armed drones for signature strikes and targeted killings on both legal and ethical grounds.[23]

However, Ukraine's fight for its sovereignty dramatically changed public attitudes in the West, making armed drones politically palatable. Once decried as flying assassination robots, armed and one-way-attack drones are now being supplied to Ukraine through various crowdfunding initiatives across European societies. National governments are also financially encouraging local companies to export drones to Ukraine.

Military commanders now prioritise drone capabilities, including loitering munitions, for adapting armed forces to future conflicts. Drones have become critical in warfare, especially when combined with long-range fires and space-based satellites.[24] The popularity of loitering munitions and one-way-attack drones stems from their ability to suppress air defences, support counter-artillery operations, and target armoured vehicles on static frontlines.[25]

Paradoxically, loitering munitions raise more ethical concerns than missile strikes from larger drone platforms during counterterrorism operations. This is due to their impact on human control over the use of force, with sensors increasingly making targeting decisions of questionable precision.[26] The rise of loitering munitions reflects the broader trend towards growing autonomy in uncrewed systems.

Table 1 highlights the increasing demand for loitering munitions and arming existing large drones across Western countries.[27] For small and less-resourced countries, drones represent an opportunity to compensate for the lack of expensive combat systems or modern precision munitions.

Table 1: Lethal Drones on the Rise

Country	Loitering Munition (Various Acquisition Stages)	Large Armed Drones (Various Acquisition Stages)
Albania		Bayraktar TB2
Australia	Switchblade-300; Drone40; OWL	
Canada		MQ-9B SkyGuardian
Estonia	IAI-MBDA portfolio	
France	Colibri; Larinae	MQ-9 Reaper
Georgia	Warmate	
Germany	IAI-MBDA portfolio; Rheinmetall-UVision portfolio	Heron TP
Greece	Hero-30	(Interested in MQ-9 Reapers)
Hungary	Rheinmetall-UVision portfolio	
Italy	Rheinmetall-UVision portfolio	
Japan	(Interested in Switchblade and\or Altius)	(Interested in Bayraktar TB2 or MQ-9 Reaper)
Kosovo		Bayraktar TB2
Lithuania	Switchblade-600	
Netherlands		MQ-9 Reaper
Poland	Warmate	MQ-9 Reaper; Bayraktar TB2
Romania		Bayraktar TB2
Serbia		CH-92A
Slovakia	(Interested)	(Interested in Bayraktar TB2)
Spain		MQ-9 Reaper
Sweden	(Interested)	
Turkey	Harpy; Harop; Alpagu; Barkan; Kargu-2; Warmate	Bayraktar TB2; Anka-S; Akinci-A
Ukraine	Phoenix Ghost; Switchblade-300; Switchblade-600; Drone40; Warmate	Bayraktar TB2
United Kingdom	Drone40; Switchblade-300	MQ-9 Reaper; MQ-9B Protector
United States	Hero-120; Phoenix Ghost; Switchblade-300; Switchblade-600	MQ-9 Reaper; MQ-8 Fire Scout

Loitering munitions have traditionally been developed and operated by China, Israel, Russia, Turkey, and the United States. In Europe, demand for loitering munitions is being met by Israeli firms like UVision, in collaboration with Rheinmetall, Israel Aerospace Industries, MBDA Germany, and Elbit Systems, which deliver SkyStriker loitering munitions. European homegrown production includes Poland's WB Electronics producing Warmate and Turkey's Kargu and Alpagut systems. France has also been working on its short-range Colibri and mid-range Larinae loitering munitions. Meanwhile, Estonia's army is considering creating a company-sized unit dedicated solely to loitering munitions and eventually equipping all infantry units with small drones.

In the United States, the rise of loitering munitions has been particularly notable due to their lower cost compared to traditional missiles or advanced drones. The US Army is developing the Low Altitude Stalking and Strike Ordnance (LASSO) programme to equip infantry brigades with man-portable precision munitions capable of destroying armoured vehicles.[28] Meanwhile, US Special Operations Command prioritises loitering capability through its Ground Organic Precision Strike System, which includes vehicle-mounted and tube-launched Switchblade 300 and 600 drones, along with UVision's Hero-120 munitions.[29] The US Marine Corps also aims to equip rifle squads and platoons with lightweight, packable loitering munitions.

> Before February 2022, only two European countries operated large drones for launching missile strikes

Before February 2022, only two European countries, the United Kingdom and France, operated large, medium-altitude, long-endurance (MALE) drones capable of launching missile strikes. Another six European countries operated only unarmed versions of such drones for ISR tasks. Following the spectacular rise of TB2 drones in recent years and their initial successes in Ukraine, several European countries rushed to either procure new large armed drones (Albania, Canada, Kosovo, Poland, and Romania) or arm their existing fleets (Germany, the Netherlands, and Spain). Notably, once a staunch opponent of armed drones, Germany has shifted its doctrine. Berlin has procured missiles for its Heron TP drones from Israel and is considering developing a fleet of small, expendable, lethal drones.[30]

However, European countries rely on foreign drone technology.[31] Despite efforts to develop domestic capabilities, the most prominent Eurodrone project – intended to create a European equivalent of the American MQ-9 – has yet to become operational. Due largely to industrial nationalism, eight of the fifteen European countries operating MALE drones rely on various versions of the American-made General Atomics MQ-9 Reaper. The remainder use Israeli drones – Germany and Greece operate the Heron, while Switzerland has acquired the Hermes 900 – or Turkish TB2 drones, adopted by Albania, Kosovo, Poland, Romania, and Ukraine. Many procurement plans are afoot. The Netherlands is doubling its fleet of MQ-9s. The UK Royal Air Force will receive sixteen US-made Protector drones for strategic surveillance at land and sea by 2025.[32] Italy is upgrading its fleet of MQ-9A Reapers for ISR missions domestically over the Mediterranean and to support NATO operations. Poland has upgraded the Mirosławiec Airbase to host MQ-9A Reaper drones operated by the US Air Force. Warsaw also plans to buy new MQ-9B drones and, while waiting for their delivery, has leased a fleet of MQ-9A Reapers from General Atomics.[33] Canada is procuring eleven MQ-9B SkyGuardians for almost 2 billion USD to monitor the High North Arctic region and its lengthy coastline by 2033. Opting for an armed version will also enable Canada to fulfil its North American Aerospace Defense Command (NORAD) obligations.[34]

Drone Intelligence

The war in Ukraine has revitalised the importance of drones with long endurance and powerful sensors, particularly for aerial surveillance over large areas. Despite incidents like the March 2023 crash of an MQ-9 Reaper over the Black Sea after a Russian Su-27 fighter jet damaged its propeller, long-range, high-altitude surveillance drones continue to collect valuable intelligence data.[35]

Demand for NATO-collected ISR data has been exponential since Russia's invasion.[36] NATO's Alliance Ground Surveillance Force, which operates five Phoenix drones based on the RQ-4D Global Hawks Block 40, provides members with common surveillance capabilities. These drones can reach Northern Finland from the Italian Sigonella Airbase, hover for hours at high altitudes – especially over the Baltic and Black Seas and Eastern Europe – and return in one sortie (up to 30 hours). They then share ISR data with all Alliance members. Furthermore, due to increased Russian military activities, the Danish government is procuring long-range ISR drones to increase Arctic and North Atlantic surveillance – also known as the strategically important GIUK gap.

Such developments are not just limited to Europe. In the Indo-Pacific, South Korea's first domestically developed medium-altitude drone, created by Korean Air Aerospace Division and Hanwha Systems, will enhance the Air Force's real-time monitoring capabilities by 2028. Meanwhile, Australia has been expanding its MQ-4C Triton fleet, manufactured by Northrop Grumman, for long-range, day-long reconnaissance missions and vast oceanic monitoring.

Ground forces have been the first to react to drone developments in the so-called air littoral (the airspace from the Earth's surface to about 5km). Observing substantially increased accessibility of drone aerial reconnaissance, the US Army, for instance, has started looking into ways to augment and upgrade its uncrewed systems instead of procuring more crewed reconnaissance aircraft (such as helicopters). It has also accelerated upgrading its short-range reconnaissance quadcopters with thermal cameras.

In terms of force structure, however, US Army leadership is sceptical about establishing a separate branch specialised in overseeing drone and counter-drone programmes. Instead, all formations across echelons are expected to operate drones and defend against the drone threat.[37] In contrast, Germany is considering creating a dedicated drone branch within its army, inspired by Ukraine's drone army experience. This new branch would address needs across air, land, and maritime domains, equipping each unit with reconnaissance drones and countermeasures.

New Approaches to Defence Innovation

Deployments of high-tech but expensive drones in contested zones under constant attack may prove financially unsustainable due to slow regeneration rates. While some governments already introduced organisational changes to encourage defence innovation in the recent past, the war in Ukraine has confirmed the need for opening conservative central bureaucracies to new supply chains and creating innovation partnerships.

Several countries have recognised that traditional acquisition processes are too slow to access cutting-edge technologies from the private sector. For instance, since 2015, the US Defense Innovation Unit (DIU) has advised military leadership on fielding new commercial technologies. Similarly, the French Ministry of Armed Forces established its Defence Innovation Agency in 2018 to capture opportunities originating in the commercial sector, while the UK Defence and Security Accelerator (DASA) funds attract commercial solutions for such challenges. In contrast, the Dutch Ministry of Defence relies on a decentralised network of regional innovation centres, hubs, and incubators built around universities and tech firms.

Various national initiatives, therefore, aim to create new infrastructure for facilitating the adoption of rapidly evolving commercial technology into defence capability. On a regional level, most notably, several NATO members agreed to launch an alliance-wide Defence Innovation Accelerator for the North Atlantic (DIANA) and NATO Innovation Fund (NIF) in 2021. To strengthen the alliance's defence and resilience, these programmes connect allied armaments directors with new industrial actors and build a trusted start-up ecosystem to harness cutting-edge technologies.[38]

Kyiv's experience may provide further ideas. Its Ministry of Defence Innovation Development Accelerator is designed to adopt innovative solutions quickly by combining capabilities within the ministry. The Brave1 platform the Government of Ukraine created supports defence start-ups and funds tech projects deemed critical for the country, including AI augmentation of drones. However, the US Replicator programme and the UK Drone Defence Strategy are the two most concrete initiatives to supply armed forces quickly, cheaply, and at scale.

> Various national initiatives aim to create new infrastructure for the adoption of commercial technology into defence capability

Since August 2023, the US Department of Defense has aimed to field disposable autonomous drones in thousands across multiple domains by August 2025. The ambition of the new Replicator initiative is thus to scale up commercial solutions for critical military operational challenges.[39] Indeed, the Pentagon has funded more than 30 different Replicator capability projects, involving DIU's lead on hardware vetting and the Chief Digital and Artificial Intelligence Office's help to identify a digital collaborative infrastructure.[40]

Similarly, the United Kingdom's new strategic document published in February 2024 details the plan for the armed forces to acquire new drone capabilities across air, land, and sea by scaling commercial technologies. Learning from Ukraine, the UK drone strategy aims to follow a 'different cost model' for drone acquisition that builds on delivery-focused innovation culture and new industry partnerships.[41] The government plans to invest £4.6 billion by 2034 to expedite the UK Armed Forces' access to uncrewed systems, including large air platforms, littoral strikes, air littoral-land strikes, and maritime drones.

Agile, low-cost drone solutions driven by rapid technological advances are crucial. French military authorities warn that the decade-long traditional acquisition process risks leaving their forces behind. The French army has partnered with local drone makers to counter this, bypassing sluggish internal development programs.[42]

Five Challenges for the West

Absorbing lessons from contemporary drone warfare comes with several challenges for Western militaries. As they adapt force structure and doctrine to integrate new drone capabilities, political and military leaders are exploring new ways to improve the drone fabric of armed forces. Ideally, these include new procurement practices, public-private partnerships, drone safety, drone defence, and AI-enabled drone autonomy.

1. Innovate, Adopt, Repeat

While several European countries have invested heavily in developing advanced drone capabilities, modern drone warfare increasingly relies on inexpensive commercial platforms that deliver significant tactical effects at a fraction of the cost.[43] Acquiring drones that are affordable, scalable, and upgradable has become a key priority for strengthening national uncrewed capabilities. Achieving this requires innovation – not only to lower costs but also to secure the best technology available. However, obtaining drones 'cheap, fast, and many' is far from straightforward, demanding innovation in both methods and resources.

Innovate

First, accessing new technologies, often originating in the private sector, requires governments to engage with new actors outside of traditional military-industrial contractors. Central state bureaucracies must work with agencies capable of tapping into the 'new defence industry' and fostering public-private partnerships to leverage commercial technologies for national security.[44] Governments must also overcome the 'Valley of Death' problem, where good ideas fail to transition into fielded products due to bureaucratic or cultural barriers.

Adopt

Second, the rapid evolution of drone technology and tactics creates a security risk for armed forces locked into multi-year procurement cycles. Obsolescence can occur before systems are fully integrated. Flexible contracting, responsive budgeting, and giving commanders some purchasing autonomy could help address this issue. However, fast-tracking procurement without compromising oversight is essential to prevent outdated and unsafe systems from being purchased.[45]

> "Modern drone warfare relies on inexpensive commercial platforms that deliver tactical effects at a fraction of the cost

There may be a mismatch in private and public incentives as well. Tech companies, particularly those funded by venture capital, are often under pressure to adopt aggressive, profit-driven business models. This can result in rushed development cycles, bypassing rigorous testing and leading to the deployment of unsafe or ineffective systems.[46] Government innovation and acquisition agencies must detect and discourage dishonest marketing practices that promote infeasible products from economic, temporal, or technical perspectives.

Conversely, adopting drone models too quickly and in an uncoordinated manner, as seen in Ukraine during the first year of the war, can lead to issues with safety and interoperability. For instance, the absence of support from Ukraine's government discouraged soldiers from scaling volunteer-made systems while facing difficulties integrating commercial drones into military systems due to interface constraints.[47] In multinational coalitions, such as NATO, military exercises have already revealed the challenges in standardising hands-on training due to the diverse drone arsenals of allied countries.

Repeat

Finally, recent drone developments present an opportunity to leverage consumer technology as a low-cost solution to generate mass and bridge capability gaps. However, this trend also underscores the importance of software-centric innovations. Procurement priorities should shift toward acquiring inexpensive, disposable hardware while increasing investment in research and development (R&D) for software, essential for maintaining quality. For instance, the software in Ukrainian drones remains effective for only about two weeks before Russia adapts its countermeasures. Meanwhile, Western defence ministries can take over a year to adopt software updates, even though innovation agencies can reduce this time lag to three months. However, even this shortened period may still be insufficient in the rapidly evolving landscape of drone warfare.[48]

2. Regulate the War-Boosted New Defence Tech Industry

Developing and operating new drone capabilities inevitably invites new types of actors and goods into the military capability architecture. This is especially true as space and cyber-enabling domains gain prominence. Much emerging technology is not developed through government-sponsored projects but is market-driven and software-based; civilian tech expertise is applied to military operational needs.

New defence tech applications

> "Much emerging technology is not developed through government-sponsored projects

In Ukraine, private tech companies provide critical digital infrastructure. They do so in terms of cloud computing (Amazon, Microsoft), communication and data sharing (Palantir), cybersecurity (CrowdStrike, FireEye), satellite imagery (Planet Labs, BlackSky Technology, Maxar Technologies) and internet connectivity (SpaceX). Similarly, Russian troops use social media messaging apps (Telegram) to collect open-source data, navigate their drones, and guide artillery. The war in Ukraine has thereby expanded the role of private defence tech firms.

Open-source Intelligence generated via civil-military sensor networks has come to represent an overwhelming majority of data fed into decision-making and targeting processes. With the rise of digitised battle command-and-control, tech companies have become central to effective drone operations.[49] There are at least four distinct reasons for this: data collection (commercial satellite services, apps), data connections (low Earth orbit satellites and telecommunications networks), data fusion and analysis (battle management systems), and data targeting (AI-enabled image classification tools).

New defence tech risks

However, embedded dangers result from private actors owning critical assets and retaining control over access to services during wartime. For instance, they can restrict product availability in certain geographical areas or make their service available to the other side of the conflict. Tech companies primarily operate in a very competitive commercial market and usually do not get involved in war for charitable reasons. In their geopolitical ignorance, private actors pursue private interests that can harm national security.[50]

Much can depend on the interests and personality of company executives. For instance, while thousands of Starlink terminals enabled military communication among Ukrainian troops, including guiding drone strikes, the leadership of SpaceX did not allow the Ukrainians to use Starlink satellites over Crimea.[51] Moreover, several NATO members had to pay for Starlink services so that Ukraine could continue using them.[52]

By contrast, when Google realised that its maps could reveal the positions of Ukrainian forces to Russian troops, it disabled traffic updates and concentration features to prevent Ukrainian operations from being exposed.[53]

Political and military leaders must design a sound cooperative framework with the emerging new defence industry addressing at least three issues. First, they must clarify the chain of command to ensure that commercial providers cannot interfere with (and compromise) military operations. Second, they need to establish clear procedures for the protection of 'tech mercenaries' supporting military operations and rigorously apply international law in conflict, adhering to principles of responsibility and accountability. Third, they must regulate commercial technology sales and control local applications to protect allies and partners (for instance, satellite imagery).[54]

3. Mitigate Drone Vulnerabilities

With experience from rapid drone deliveries to Ukraine, Western governments are learning to meet capability demands within days. However, armed forces adopting new drone technology must tackle three key vulnerabilities: digital footprints, cybersecurity, and platform fragility.

Drone footprints

Drones can turn into a security liability. Airborne drones can reveal a unit's position when the adversary deploys basic hand-held sensors. They can detect drones at a distance and scan the electromagnetic spectrum for signals. Such drone signatures are becoming the new cigarette in the trenches. Armed units need to be mindful of their digital footprint. This means minimising data left behind, data storage exposure, and location tracking. For instance, after Ukrainian troops realised that DJI Mavic drones turned into a 'hazardous encumbrance' due to Russia's use of the AeroScope drone detection system, they developed a software update to hide from radio emissions trackers, as well as their drone platforms, such as R18 octocopter.[55]

> "Militaries should field only commercial drones from verified suppliers

Cybersecurity

Military planners must align open digital architecture with resilient communication networks to connect and integrate drones operationally across domains and joint forces. Given the omnipresence of EW that can interfere with drone command and control, consumer electronics in drones need better cyber protection to perform battlefield tasks. Hostile actors can exploit data to spy, steal, compromise networks, and enhance their strike abilities.

Militaries should field only commercial drones from verified suppliers compliant with cybersecurity standards. The US has followed this vetting process since 2020, after a 2018 ban on purchasing Chinese drones for military use. This has necessitated indigenous innovation since the commercial drone market – including components manufacturing – has been dominated by Chinese company DJI for over a decade. DIU issued a so-called Blue UAS initiative, which lists commercial systems for the military that passed cyber vulnerability assessment and airworthiness approvals.[56] This database of secure and verified consumer drones is part of the Pentagon's efforts to scale up commercial drone technology. For instance, the Blue UAS list corroborates the integration of inexpensive small drones under the aforementioned US Army Short Range Reconnaissance programme.

Platform fragility

Drones also have a poor survivability record in harsh weather and EW-heavy environments. Low-cost drones made of commercial technology have similar specifications to consumer electronics. Hence, user manuals usually caution customers to handle the drone with care. Strong winds, morphology of the terrain, and low temperatures significantly affect drone performance and reliability. For instance, sub-zero temperatures shorten battery life, seriously limiting range or even causing the drone to drop, and they can also freeze the drone's camera.

The electromagnetic spectrum also imposes key limits on drone operations. For instance, there may be insufficient bandwidth to navigate many airborne drones simultaneously. Furthermore, drones can be easy prey. The war in Ukraine revealed that Russian EW tempered expectations of drone technological miracles. Intense jamming can reduce the strike rate of FPV drones to only 30 to 50 per cent.[57]

Mitigating drone vulnerabilities can compromise the objective of low purchase and operating costs. Vetted drone companies on the Blue UAS list usually offer more expensive drones than regular civilian manufacturers that do not collaborate with the military and require cybersecurity certification.[58] Additional protective features, such as anti-jamming devices, can increase the cost of a single drone by thousands of dollars. This can drastically alter the cost-benefit calculus of procurement and operations strategies.

> "The high costs of drone detection and interception remain the biggest challenges in developing effective countermeasures

These vulnerabilities imply that saturating the air above the battlespace with cheap quadcopters is not a viable winning strategy. Drones cannot enforce air superiority or sustain combat power under attack. While drones can delay the offensive, destroy infrastructure, frustrate air defences, and intimidate enemy troops, they do not have the firepower to take territory or destroy strongholds.

Drones are also not natural extensions of human combatants. While they offer capability gains, they reduce force structure efficiency. Although technology can take over dangerous, dull, or dirty tasks, personnel such as operators, technicians, data analysts, communication specialists, software engineers, and force protection units are still required on the battlefield.[59]

4. Lay(er) Out Drone Defences

Contemporary drone warfare has demonstrated the rapid spread of drones and the significant threat posed by new deployments. While the commercial drone market is advancing rapidly, technology and tactics to counter drones have a long way to go. Addressing threats like swarms and greater autonomy will likely require changes to current defence systems and force structures. The high costs of drone detection and interception remain the biggest challenges in developing effective countermeasures.[60]

Challenging drone threat

Consumer drones, built from off-the-shelf materials such as cardboard, plastic, and plywood, fly at extremely low altitudes with minimal radar visibility. As drone numbers increase on the battlefield, defence systems must detect and track multiple simultaneous attacks, differentiate between friendly and hostile drones, and assess whether enemy drones are decoys or equipped for surveillance or strikes. A recent example involved a drone from an Iran-based militia that struck a US base in Jordan, killing three soldiers. Air defences either misidentified the drone as friendly or hesitated due to the simultaneous return of an American drone.[61]

The cost ratio strongly favours the offence. Drones are much cheaper to produce and operate than the cost of defending against them and the damage they can cause. As drone technology has reduced the cost of precision-guided munitions and eased production pressures, the defending side launches multi-million-dollar missiles to neutralise drones that cost only a few hundred dollars.

The organisation of air defence responsibilities across the armed services must reflect the widening spectrum of aerial threats and targeting ambiguity. Yet, the two new approaches to drone capability development mentioned above (US Replicator, UK Drone Defence Strategy) focus on the offensive use of small drones without addressing the drone threat. In contrast, between October 2023 and January 2024 alone, US bases and coalition facilities were attacked 150 times in Iraq and Syria.

In Europe, building drone countermeasures is urgent yet complicated due to capability gaps. The situation is slowly improving. More countries are now procuring mobile short-range air defences. Germany and Denmark are buying Rheinmetall's Skyranger, armed with a 30mm air defence cannon and Stinger missiles to protect troops against missiles and low-flying drones. The Dutch Army has created several platoons dedicated to countering drones, including medium-range air defence.[62] Swedish armed forces are procuring wearable drone countermeasure systems for mobile units, such as Danish-made Wingman and Pitbull, for drone detection and disruption.

> “The cost ratio strongly favours the offence

There are also collaborative endeavours among allies. In addition to the German-led European Sky Shield Initiative, a group of Northern and Eastern European countries is working to set up infrastructure to protect the borders from Norway to Poland against drones, as well as cruise and ballistic.[63] NATO has been actively collecting best practices to prepare a counter-drone doctrine and adopting the SAPIENT protocol developed in the United Kingdom to leverage an open-architecture multi-sensor fusion for countering drones.[64]

Drone countermeasures continuum

Drone countermeasures in specialised air defence formations and overseas bases differ from those used by manoeuvring forces. Securing air defences at a military base requires a layered approach, combining passive and active systems, often relying on long-range interceptors and prioritising area defence. By contrast, mobile units favour compact, portable solutions such as hand-held guns and nets for point defence.[65]

The most effective drone countermeasures come in multi-layered air defence systems that combine kinetic and non-kinetic measures. These are best complemented with anti-drone strategies integrated at every level of command. Indeed, US military leadership is considering implementing the layered approach to protect its overseas bases. Drone defences would combine a wide, invisible EW perimeter to spoof the hostile drone while a closer layer of microwave weapons would fry the drone from the inside. The final layered component would comprise a hard-kill system involving shooting the drone with a small missile or machine gun.[66]

Diversifying drone countermeasures is justified by rapid innovation-adaptation cycles. While EW once seemed like unbeatable supernatural magic, electronic jammers can cover only a narrow frequency spectrum range. Jammer units and drones are essentially forced to play a catch-up game. This also means the attacker can overpower the jammer-based defences if each attacking drone operates on a different frequency. Further, jamming loses its teeth once drones begin to operate autonomously.

If autonomous navigation is an antidote to EW, then directed-energy weapons might become the antidote to AI-enabled drones. These weapons would target drone optical and radio frequency sensors and electronics by either using high-energy lasers (to melt critical components) or electromagnetic systems with different wavelengths (disabling or reducing the effectiveness of sensors and electronics).[67] The most promising advantage of directed-energy weapons lies in countering saturation attacks. Targeting electronics could neutralise multiple drones at a fraction of the costs of the drone swarm and thus rebalance the drone offence-defence cost asymmetry.[68] Yet, the most effective counter-drone action may be defeating the drone before it gets airborne.

On the active battlefield, doctrinal developments for countering drone threats have progressed. Just one decade ago, 'seeing and hearing' was the primary capability to detect small drones. Special tracking and identification devices using networking sensors for low-level air threats are standard today. This is a massive advance, but the drones appear to be changing faster than countermeasures can keep pace. While armed forces adapt their structure to drone threats by increasing dedicated air defences, it is expected that all troop levels will need to pass counter-drone training to acquire defensive skills.

These may also include passive defences, such as camouflage or protective construction – like cope cages on Israeli Merkava tanks or metal grilled roofs on Ukrainian 'turtle' tanks. Importantly, the persistent presence of monitoring sensors above the battlefield has shrunk the area for safe troop manoeuvres of large mechanised formations and encouraged dispersing troops and concealing equipment. Lastly, deception tactics can employ realistic decoys to replicate key equipment and emit electromagnetic signatures to produce noise.

5. Master Algorithmic Warfare

> AI on the battlefield is still searching for its definitive role

The ability to implement digital technologies and scale AI systems on the battlefield is becoming crucial for the future of drone warfare. By addressing the complexity and cost of sophisticated drones, AI is expected to enhance *software quality* to support the increasing *hardware quantity* of drones. The military potential of AI appears to be highly versatile. AI-powered systems could improve decision-making by gathering and analysing near-real-time data at superhuman speeds and scales, enabling rapid responses to incoming threats by automating data processing and analysis. Several AI systems have already been successfully deployed for social media analysis to combat disinformation campaigns. Additionally, AI models can assist logistics by optimising resource allocation and supply chains. However, due to ongoing uncertainties, AI on the battlefield is still searching for its definitive role.

Drone-driven AI on the battlefield

Contemporary drone warfare demonstrates that drones are driving experimentation with AI on the battlefield, primarily in two areas: autonomous targeting and swarm command. AI object recognition can help drones with terrain mapping and identifying targets. Given that drone warfare is also characterised by an operational environment disrupted by extensive EW, enhancing drones with AI can offer a way to continue the mission even under jamming since there is no navigation or communication link for the attacker to disrupt. In comparison, overcoming jamming with traditional fire-and-forget autonomy is ineffective against moving targets.

Drones guided by AI, though relatively crude, are already available to army commanders today.[69] For instance, Ukraine's Saker drone can find and lock onto a target thanks to AI object recognition (the human still needs to confirm the target). Using AI to classify information, the French company Preligens developed the software Robin for image analysis and Xerus for military terrain mapping to distinguish between civilian and military objects, site monitoring, and pattern-of-life analysis. The Israeli AI system Lavender uses machine learning to sift through data to find targets for airstrikes, automating the identification process and cross-checking.

A second type of AI use aims to advance the ability of a single operator to command several drones simultaneously. For instance, the Styx software from the Swarmer company in Ukraine will create a network of drones that can implement commands across all drones. This would reduce the personnel required to operate uncrewed systems while increasing the number of airborne drones.[70] In principle, using multiple drones – individual or AI-coordinated – can be an attractive and cheap option not only for terrorists but also for state actors to gather intelligence or overwhelm enemy air defences.[71]

AI and autonomy limitations

However, military AI applications have inherent safety limitations largely due to data scarcity and the nature of war. First, AI-enabled drones are better at tracking infrared and powerful radar signals than performing visual image recognition. Research has shown that tiny picture alterations can change how AI classifies them.[72] This is related to the second point. Due to its inherent instability, war lacks patterns and reliable data for training and iteration. Moreover, AI data-driven learning algorithms have no conceptual understanding of the context; they have pattern identification, not situational awareness. This makes existing AI systems vulnerable to rogue adversarial inputs intended to confuse and disable them.

> “Developing new technology alone does not yield capability with comparative advantages vis-à-vis existing adversarial capabilities

In the long term, the integration of new uncrewed systems is already considering the promise of future AI. Most notably, efforts at teaming machines with humans as loyal wingmen are meant to meet force structure shortfalls and improve combat strength.[73] Developing low-cost, expendable drone capabilities for future warfare will be crucial for Western forces that may enjoy neither air superiority nor persistent technological advantage in AI, autonomy, and computing.[74]

Future drones are on the horizon. These systems, known as autonomous collaborative platforms, are believed to enable operations in denied environments. They may do so while keeping crewed aircraft out of the danger zone, serving as ears and eyes (surveillance), flying missile magazines (strikes), or jamming boxes (EW tool). Some national examples of these efforts include the Tempest project by Italy, Sweden, the United Kingdom and the US Next Generation Air Dominance (NGAD) programme.

However, the successful fielding of such drones may be hindered by the lack of military trust in AI-enabled autonomous systems. The challenge is rather complex: Strike the right balance between machine autonomy, effective team mission performance, and parameters for meaningful human control.

Autonomy certainly raises some ethical questions for drone warfare. The human operator has only a few seconds after an AI system identifies the target to decide whether to strike. It will be crucial to determine the type of situations in which the operator will be required to make decisions for the machine (in-the-loop), to supervise the machine’s actions (on-the-loop), and only to spectate (out-of-the-loop). Furthermore, human combatants teamed with autonomous drones will require proper training to address automation bias, that is, the intuitive inclination to either uncritically trust the machine despite its mistakes or become unreasonably suspicious of its abilities. Overall, developing new technology alone does not yield capability with comparative advantages vis-à-vis one’s own – or adversarial – existing capabilities.

Conclusion

Recent developments have transformed the character of drone warfare. These dynamics are a far cry from arguments made about the continuity of other elements of conflict, given the lessons of Russia's war on Ukraine.[75] In contrast to previous drone wars, small, inexpensive, and commercially available drones dominate contemporary drone operations. FPV drones offer mass and precision at low cost, improving operational resilience and raising the price of aggression. In turn, without air superiority, armed forces cannot succeed without well-integrated and multi-layered air defences, as well as protected mobile air defence systems.

Western militaries are paying attention. The initial signs of changes in force structure and doctrine have been relatively modest. Several countries have embarked on a shopping spree for loitering munitions, created new drone innovation ecosystems, and overhauled their procurement procedures, following the mantra of 'cheap, many, and fast'. Political-military authorities need to further cultivate relationships with new tech firms outside the traditional defence industry and set the right parameters for collaboration. New leaders in the defence tech industry may struggle to separate their private, profit-driven motives from the interests of troops aiming to win battles or the international community's priorities for responsible and regulated use of repurposed civilian technologies.

> "The success of any drone strategy hinges on realistic expectations of their impact

While drones are thought to herald the era of AI warfare, contemporary drone warfare has shown only limited military applications of AI on the battlefield. So far, AI has proven far more useful in supporting decision-making processes at digitised military headquarters. Yet, the most difficult part of the learning process from contemporary drone warfare might be expectation management about drone capabilities. Emerging technologies are often prone to have their future capabilities exaggerated. However, today's drone technological and tactical developments may offer key insights for tomorrow's conflicts and defence innovation.

First, innovation and integrating new technology into the military faster than the adversary is not the full success story. If small drones empower the individual soldier, then the success of drones highlights the tech-savviness of their human operators. Thus, investing in new human skillsets and meeting the talent deficit, as well as making organisational changes to adopt new defence technologies coming from the commercial sector, are the new prerequisites for a country to enjoy a true technological edge.[76] Uncrewed systems are about much more than the platform. They rely on the deliberate integration of components in their payloads, software, and supporting networks alongside critical human skills. Restructuring to embrace new technologies and future-proof armed forces should be incremental for the change to last and be effective.

Second, the success of any drone strategy hinges on realistic expectations of their impact. Deployments must be planned accordingly. Drones can degrade an adversary's capabilities and slow offensives but cannot reclaim lost territory. They enhance and support conventional forces yet cannot replace crewed aircraft squadrons. Their effects are tactical rather than radical.[77] Drones are not revolutionary in shaping war outcomes.[78] While AI-powered drones may provide a strategic edge, their advantage endures until an adversary fields superior drones or cost-effective countermeasures.

The war in Ukraine has shown the advantages of disposable drones, falling costs, and accessibility of small, uncrewed systems, making lower airspace the centre of air warfare. However, as the Air Force's task is to gain and maintain control of the skies, it remains unclear how best it can integrate low-cost airpower assets. The urgent question, therefore, is not whether the Air Force should invest in survivable drone platforms at the expense of small disposable ones. The immediate battlefield dilemma concerns task division among armed services – who controls air superiority and who manages air defence.[79]

Such questions are also likely to arise in debate over the future of navy and naval warfare.[80] Maritime drones are already fighting Russian warships in the Black Sea, and Houthis are deploying drone boats to attack shipping vessels in the Red Sea. Any future doctrinal adaptation and integration of new drone capabilities must factor in the spread of uncrewed systems across the land, air, and sea domains.

Endnotes

1 Bremer, Maximilian K., and Kelly A. Grieco. 2024. “To Reinvent Itself, the US Air Force Must Go Big on Small Drones.” *Defense News*, 2 April. https://www.defensenews.com/opinion/2024/04/02/to-reinvent-itself-the-us-air-force-must-go-big-on-small-drones/.

2 Lushenko, Paul, and Shyam Raman. 2024. *The Legitimacy of Drone Warfare: Evaluating Public Perceptions*. London: Routledge.

3 Kunertova, Dominika. 2023. “Drones Have Boots: Learning from Russia’s War in Ukraine.” *Contemporary Security Policy* 44(4): 576–591. doi:10.1080/13523260.2023.2262792.

4 Chávez, Kerry, and Ori Swed. 2023. “Emulating Underdogs: Tactical Drones in the Russia-Ukraine War.” *Contemporary Security Policy* 44 (4): 592–605. doi:10.1080/13523260.2023.2257964.

5 Chávez, Kerry. 2023. “Learning on the Fly: Drones in the Russian-Ukrainian War.” *Arms Control Today*, (January/February).

6 C-UAS Hub. 2023. “Hamas 7th October Intrusion: Drones Observed.” *DroneSec*, 8 October. https://cuashub.com/en/content/dronesec-update-hamas-use-of-drones/.

7 Basit, Abdul, and Rueben Dass. 2024. “Tech and Terror: Why Have Drones Not Penetrated the Afghanistan-Pakistan Militant Landscape?” *GNET Insights*, 29 April. https://gnet-research.org/2024/04/29/tech-and-terror-why-have-drones-not-penetrated-the-afghanistan-pakistan-militant-landscape/.

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

9 Kunertova, Dominika. 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. doi:10.1080/00963402.2023.2178180.

10 FPV drones have powerful motors and improved navigation adapted for high-speed races and demanding maneuvers. On the battleground, immersive goggles enable human pilots to send these high-performing and explosive-laden drones to their targets with precision. See also: Milasauskas, Tomas, and Liudvikas Jaškūnas. 2024. “FPV drones in Ukraine are changing modern warfare.” Atlantic Council, 20 June. https://www.atlanticcouncil.org/blogs/ukrainealert/fpv-drones-in-ukraine-are-changing-modern-warfare/

11 Plichta, Marcel, and Ash Rossiter. 2024. “A One-Way Attack Drone Revolution? Affordable Mass Precision in Modern Conflict.” *Journal of Strategic Studies*, August, 1–31. doi:10.1080/01402390.2024.2385843.

12 Hambling, David. 2023. “Could Small Drones Really Replace Artillery?” *Forbes*, 16 August. https://www.forbes.com/sites/davidhambling/2023/08/16/could-small-drones-really-replace-artillery/

13 Watling, Jack, and Nick Reynolds. 2023. *Meatgrinder: Russian Tactics in the Second Year of Its Invasion of Ukraine*. RUSI, 19 May. https://rusi.org/explore-our-research/publications/special-resources/meatgrinder-russian-tactics-second-year-its-invasion-ukraine.

14 Steavenson, Wendell. 2023. “Ukraine’s Bog Warriors Brave Swamps, Stench and Russian Drones.” *1843 Magazine*, 21 July. https://www.economist.com/1843/2023/07/21/ukraines-bog-warriors-brave-swamps-stench-and-russian-drones.

15 Vandiver, John. 2023. “Cheap Drones Have Yielded ‘Huge Results’ for Ukraine, US general in Top NATO Role Says.” *Stars and Stripes*, 27 September. https://www.stripes.com/theaters/europe/2023-09-27/eucom-cavoli-ukraine-drones-11510485.html.

16 Denisova, Kateryna. 2023. “Griselda. A System of Intelligence Based on Artificial Intelligence Has Been Developed in Ukraine.” *NV*, 20 October. https://nv.ua/ukr/ukraine/events/v-ukrajini-na-bazi-shtuchnogo-intelektu-rozrobili-sistemu-rozvidki-50362114.html.

17 Goncharuk, Vitaliy. 2024. “Survival of the Smartest? Defense AI in Ukraine.” In: Borchert, Heiko, Torben Schütz, and Joseph Verbovszky, (eds.). *The Very Long Game*. Springer, Cham, 375–395. https://doi.org/10.1007/978-3-031-58649-1_17.

18 DeVore, Marc R. 2023. “‘No End of a Lesson:’ Observations from the First High-Intensity Drone War.” *Defense & Security Analysis* 39(2): 263–66. doi:10.1080/14751798.2023.2178571.

19 Fornusek, Martin. 2024. “Zelensky signs law establishing Ukraine’s Unmanned Systems Forces.” *The Kyiv Independent*, 16 September. https://kyivindependent.com/zelensky-signs-law-on-ukraines-unmanned-systems-forces/

20 Stack, Jason. 2024. “To Achieve Replicator, the Pentagon Should Mirror Unmanned Task Force.” *Defense News*, 8 March. https://www.defensenews.com/opinion/2024/03/08/to-achieve-replicator-the-pentagon-should-mirror-unmanned-task-force/.

21 Kunertova, "The War in Ukraine Shows the Game-Changing Effect of Drones Depends on the Game."

22 Kunertova, Dominika. 2022. "The Ukraine Drone Effect on European Militaries." *CSS Policy Perspectives* 10(15).

23 Kennedy, Greg. 2013. "Drones: Legitimacy and Anti-Americanism." *Parameters* 43(1); Keating, Vincent C. 2022. "Membership has its Privileges: Targeted Killing Norms and the Firewall of International Society." *International Studies Quarterly* 66(3): sqac040.

24 Insinna, Valerie. 2022. "Drones, sats and rockets: As Sweden Looks to Boost Spending, It's Taking Lessons from Ukraine." *Breaking Defense*, 19 December. https://breakingdefense.com/2022/12/drones-sats-and-rockets-as-sweden-looks-to-boost-spending-its-taking-lessons-from-ukraine/.

25 Goldstein, Lyle, and Nathan Waechter. 2023. "Chinese Strategists Evaluate the Use of 'Kamikaze' Drones in the Russia-Ukraine War." *RAND Commentary*, 7 November. https://www.rand.org/pubs/commentary/2023/11/chinese-strategists-evaluate-the-use-of-kamikaze-drones.html.

26 Bode, Ingvild, and Tom Watts. 2023. *Loitering Munitions and Unpredictability: Autonomy in Weapon Systems and Challenges to Human Control*. Center for War Studies, University of Southern Denmark. https://usercontent.one/wp/www.autonorms.eu/wp-content/uploads/2023/06/Loitering-Munitions-Unpredictability-WEB.pdf?media=1629963761.

27 This table summarises open-source data compiled by the author from media news articles and databases, including: Watts, Tom, and Ingvild Bode. 2023. *Automation and Autonomy in Loitering Munitions Catalogue (v.1).* Accessed 10 July. https://zenodo.org/records/7860762#.ZEdaG3bMLre; Hinz, Fabian, and Tom Waldwyn. 2024. "Europe comes full circle on loitering munitions." *IISS Military Balance Blog*, 2 February. https://www.iiss.org/en/online-analysis/military-balance/2024/01/europe-comes-full-circle-on-loitering-munitions/ ; Cole, Chris. 2024. "Who has Armed Drones?" *Dronewars.net*, February. https://dronewars.net/who-has-armed-drones/ ; and Kunertova, Dominika. 2019. *Military Drones in Europe*. Odense: Center for War Studies, University of Southern Denmark. https://findresearcher.sdu.dk/ws/portalfiles/portal/159305039/CWS_Military_Drones_in_Europe_Report.pdf.

28 Rosenberg, Zach, and Meredith Roaten. 2023. "US Army Seeking Tube-launched, Anti-armour UAVs." *Jane's*, 24 July. https://www.janes.com/defence-news/news-detail/us-army-seeking-tube-launched-anti-armour-uavs.

29 White, Andrew. 2023. "USSOCOM Eyes Loitering Systems For EW, Other Functions." *Jane's*, 15 May. https://www.janes.com/osint-insights/defence-news/air/ussocom-eyes-loitering-systems-for-ew-other-functions.

30 Martin, Tim. 2024. "Diehl Close to FEANIX Drone Deal with Germany, Says Project Lead." *Breaking Defense*, 5 June. https://breakingdefense.com/2024/06/diehl-close-to-feanix-drone-deal-with-germany-says-project-lead/.

31 Kunertova, Dominika. 2021. "European Drone Clubs Stall Strategic Autonomy." *CSS Policy Perspectives* 9(5).

32 Financial Times. 2023. "Cost of UK's New Fleet of Armed Drones Jumps 40%." 19 September, https://www.ft.com/content/75e704e9-7d09-4d93-9fea-82404e89e1dd.

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

34 Canadian Department of National Defence. 2023. "Canada Acquiring Remotely Piloted Aircraft Systems for the Canadian Armed Forces." Press Release, 19 December. https://www.canada.ca/en/department-national-defence/news/2023/12/canada-acquiring-remotely-piloted-aircraft-systems-for-the-canadian-armed-forces.html.

35 Similarly, in the Middle East in November 2023, Iranian-backed Houthis Rebels Shot Down a US MQ-9 Drone over the Red Sea. Babb, Carla. 2023. "Houthis Shot Down US Drone Over Red Sea." *Voice of America News*, 9 November. https://www.voanews.com/a/us-official-to-voa-houthis-shot-down-us-drone-over-red-sea-/7347772.html.

36 Mabeus-Brown, Courtney. 2024. "Eyeing the Storm: Air Force's 'Hurricane Hunters' are Busier than Ever." *Air Force Times*, 6 May. https://www.airforcetimes.com/news/your-air-force/2024/05/06/eyeing-the-storm-air-forces-hurricane-hunters-are-busier-than-ever/.

37 Albon, Courtney. 2024. "Drone Corps Proposal Would Disrupt US Army Plans, says Undersecretary." *Defense News*, 17 May. https://www.defensenews.com/unmanned/uas/2024/05/17/drone-corps-proposal-would-disrupt-us-army-plans-says-undersecretary/.

38 Herzog, Stephen, and Dominika Kunertova. 2024. "NATO and Emerging Technologies: The Alliance's Shifting Approach to Military Innovation." *Naval War College Review*, Spring Issue (*Forthcoming*).

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

40 Albon, Courtney. 2024. "Pentagon begins awarding contracts for next round of Replicator." *Defense News*, 8 August. https://www.defensenews.com/pentagon/2024/08/08/pentagon-awards-contracts-for-second-round-of-replicator-systems/

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

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

43 Kunertova, Dominika. 2024. "Europe's Military Drone Problem." In: Rogers, James (ed.), *De Gruyter Handbook on Drone Warfare*. Berlin, Boston: De Gruyter, 299-312.

44 Béraud-Sudreau, Lucie. 2024. "Europe's Other Arms Production Problem: 'New Defense'." *EconPol Forum* 25(4), July. https://www.cesifo.org/DocDL/econpol-forum-2024-4-beraud-european-defense.pdf.

45 Skove, Sam. 2024. "Army Announces Plan to Help Spread Commercial Drones Across Infantry Units." *Defense One*, 27 March. https://www.defenseone.com/threats/2024/03/army-announces-plan-help-spread-commercial-drones-across-infantry-units/395260/.

46 González, Roberto J. 2024. *How Big Tech and Silicon Valley are Transforming the Military-Industrial Complex*. Watson Institute of International and Public Affairs, Brown University, 17 April. https://watson.brown.edu/costsofwar/files/cow/imce/papers/2023/2024/Silicon%20Valley%20MIC.pdf.

47 Jones, Seth G., Riley McCabe, and Alexander Palmer. 2023. *Ukrainian Innovation in a War of Attrition*. Center for Strategic and International Studies, 27 February. https://www.csis.org/analysis/ukrainian-innovation-war-attrition

48 Carberry, Sean. 2024. "DIU Clearing More Drones for Military Use." *National Defense Magazine*, 17 July. https://www.nationaldefensemagazine.org/articles/2024/7/17/diu-clearing-more-drones-for-military-use.

49 Hinote, Clint, and Mick Ryan. 2024. *Empowering the Edge: Uncrewed Systems and the Transformation of US Warfighting Capacity*. Special Competitive Studies Project. https://www.scsp.ai/wp-content/uploads/2024/02/SCSP-Drone-Paper-Hinote-Ryan.pdf.

50 Kunertova, Dominika, and Stephen Herzog. 2024. "Emerging and Disruptive Technologies Transform, but Do Not Lift, the Fog of War: Evidence from Russia's War on Ukraine." In Pentti Forsström (ed.), *Russia's War Against Ukraine – Complexity of Contemporary Clausewitzian War*. Helsinki: Finnish National Defence University. [Forthcoming].

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

52 Maidenberg, Micah, and Matthew Luxmoore. 2023. "Pentagon Agrees to Pay SpaceX for Satellite Internet in Ukraine." *The Wall Street Journal*, 1 June. https://www.wsj.com/articles/pentagon-agrees-to-pay-spacex-for-satellite-internet-in-ukraine-2bdf3bf4.

53 Sanchez, Irene, and Jose Ignacio Torreblanca. 2023. *Ukraine one year on: When tech companies go to war*. European Council on Foreign Relations, 7 March. https://ecfr.eu/article/ukraine-one-year-on-when-tech-companies-go-to-war/.

54 O'Connor, Michael, and Kathleen Curlee. 2024. *Eyes Wide Open: Harnessing the Remote Sensing and Data Analysis Industries to Enhance National Security*. Center for Security and Emerging Technology, July. https://cset.georgetown.edu/publication/eyes-wide-open-harnessing-the-remote-sensing-and-data-analysis-industries-to-enhance-national-security/.

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

56 Defense Innovation Unit. 2024. "Blue UAS Cleared List." https://www.diu.mil/blue-uas-cleared-list.

57 Hunder, Max. 2024. "Ukraine Rushes to Create AI-enabled War Drones." *Reuters*, 18 July. https://www.reuters.com/technology/artificial-intelligence/ukraine-rushes-create-ai-enabled-war-drones-2024-07-18/.

58 Albon, Courtney. 2024. "Drone Corps Proposal Would Disrupt US Army Plans, Says Undersecretary." *Defense News,* 17 May. https://www.defensenews.com/unmanned/uas/2024/05/17/drone-corps-proposal-would-disrupt-us-army-plans-says-undersecretary/.

59 Watling, Jack. 2024. "Automation Does Not Lead to Leaner Land Forces". *War On The Rocks*, 7 February. https://warontherocks.com/2024/02/automation-does-not-lead-to-leaner-land-forces/.

60 Kunertova, Dominika, and James Rogers. 2022. *The Vulnerabilities of the Drone Age: Established Threats and Emerging Issues Out to 2035*. NATO Science for Peace and Security Programme. https://css.ethz.ch/content/dam/ethz/special-interest/gess/cis/center-for-securities-studies/pdfs/NATO_VDA_Policy_Report.pdf.

61 Youssef, Nancy A., Michael R. Gordon, and Sune Engel Rasmussen. 2024. "US Failed to Stop Attack in Jordan After Mix-Up Over Drone Identity." *The Wall Street Journal*, 29 January. https://www.wsj.com/world/middle-east/iranian-allies-brace-for-u-s-response-to-deadly-drone-strike-99378749?mod=hp_lead_pos1.

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

63 Ostiller, Nate. 2024. "Baltics, Poland, Other Countries Agree to Create 'Drone Wall'." *Kyiv Independent*, 25 May. https://kyivindependent.com/lithuanias-interior-minister-says-group-of-countries-including-baltic-states-poland-have-agreed-to-create-drone-wall/.

64 Daleo, Jack. 2023. "NATO set to Adopt British MOD Standard for Counter-Drone Technology." *Flying Mag*, 25 September. https://www.flyingmag.com/nato-set-to-adopt-british-mod-standard-for-counter-drone-technology/.

65 Shaikh, Shaan, Tom Karako, and Michelle McLoughlin. 2023. *Countering Small Uncrewed Aerial Systems: Air Defense by and for the Joint Forces*. Center for Strategic and International Studies, 14 November. https://www.csis.org/analysis/countering-small-uncrewed-aerial-systems#new_tab.

66 Brook, Tom Van den. 2024. "No. 1 threat: Drone Attacks Prompt Urgent $500 Million Request from Pentagon." *USA Today*, 29 April. https://www.usatoday.com/story/graphics/2024/04/27/drone-attacks-urgent-500-million-request-pentagon/73347448007/.

67 Center for Arms Control and Non-Proliferation. 2024. *Directed Energy Weapons*. 14 June. https://armscontrolcenter.org/fact-sheet-directed-energy-weapons/.

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

69 Bode and Watts, *Loitering Munitions and Unpredictability*.

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

71 Kallenborn, Zachary, Gary Ackerman, and Philipp C. Bleek. 2022. "A Plague of Locusts? A Preliminary Assessment of the Threat of Multi-Drone Terrorism." *Terrorism and Political Violence* 35(7): 1556–1585.

72 Adam, David. 2024. "Lethal AI Weapons Are Here: How Can We Control Them?" *Nature*, 23 April. https://doi.org/10.1038/d41586-024-01029-0.

73 Lee, Caitlin, and Mark A. Gunzinger. 2022. *The Next Frontier: UAVs For Great Power Conflict*. The Mitchell Institute for Aerospace Studies, Air, and Space Forces Association, Arlington, Virginia.

74 Kaushal, Sidharth, *et al*. 2024. *Leveraging Human–Machine Teaming*. Royal United Services Institute, London, https://www.scsp.ai/wp-content/uploads/2024/01/human-machine-teaming-sr-jan-2024.pdf.

75 Bollfrass, Alexander K., and Stephen Herzog. 2022. "The War in Ukraine and Global Nuclear Order." *Survival* 64(4): 7–32; Willett, Marcus. 2022. "The Cyber Dimension of the Russia–Ukraine War." *Survival* 64(5): 7–26.

76 Kahn, Lauren A. 2024. "Risky Incrementalism: Defense AI in the United States." In: Borchert, Heiko, Torben Schütz, and Joseph Verbovszky (eds.). *The Very Long Game*: 25 Case Studies on the Global State of Defense AI. Springer, Cham, 39–61.

77 Kunertova, "The War in Ukraine Shows the Game-Changing Effect of Drones Depends on the Game."

78 Lushenko, Paul. 2024. “Cult of the Drone: At the Two-year Mark, UAVs Have Changed the Face of War in Ukraine - But Not Outcomes.” *The Conversation*, 16 February. https://theconversation.com/cult-of-the-drone-at-the-two-year-mark-uavs-have-changed-the-face-of-war-in-ukraine-but-not-outcomes-221397

79 Lucas, Clifford. 2024. “The Drone Dilemma and The US Air Force.” *War on the Rocks*, 7 May. https://warontherocks.com/2024/05/the-drone-dilemma-and-the-u-s-air-force/.

80 Dunley, Richard. 2024. “Small Mobile Pieces of National Sovereignty? - Uncrewed Vessels, Naval Diplomacy, and the Challenge of Signaling.” *Naval War College Review* 77(1): 15–34.

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