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ABSTRACT
The Russian invasion of Ukraine has led to the first large-scale, high intensity war where both sides have extensively deployed military and commercial drones. What the conflict has so far highlighted is that the frequently mentioned "game-changing effect" of drones on warfare depends on the game. Based on their category, drones produce distinctive military effects either as an extension of air power or as ammunition. Military thinking is therefore changing, making armed drones more politically acceptable. There is also reduced focus on the large armed and surveillance drones known from counterterrorism operations, as better integrated small drone scouts now serve land forces in combat. Far from being a mere security nuisance, small drones have yet to be effectively countered with air defenses. Military and dual-use export controls require adaptation to keep pace with these evolving battlefield realities. The drone lessons of the war in Ukraine thus point to many future challenges lying in wait for the international community.

KEYWORDS
Drones; Ukraine; military innovation; loitering munitions; emerging technology; proliferation

On the final night of 2022, Ukrainian quadcopters buzzed over the frontline town of Bakhmut and dropped bomblets on Russian soldiers across the battlefield. With thermal imaging cameras that enabled them to identify targets in pitch black conditions, these small drones flew unspotted. Meanwhile, halfway across the country in the Kyiv Oblast, dozens of Russian loitering munitions struck Ukrainian energy facilities and apartment complexes, killing up to four and psychologically terrorizing the civilian population.

These events are hardly isolated incidents. Drones have become an established part of conventional warfare in recent years. Russia's war on Ukraine also shows that these uncrewed remotely controlled vehicles are a necessary, but not sufficient, capability for achieving victory in contemporary conflicts. The "game-changing effect" of drones, evoked by the media every time a new type of drone is spotted on the battlefield, however, depends on how one defines the game. This nuance helps differentiate between drones as a capability projecting airpower and drones as single-use ammunition.

The large drones seen in counterterrorism operations in Afghanistan, Iraq, Pakistan, Somalia, Syria, and beyond, for example, do not appear to be the right systems for the war in Ukraine. The use of these drones in air operations is most effective in uncontested airspaces during asymmetric conflicts—thanks to their long endurance to perform surveillance and remote strikes. But these large aerial systems become fragile in active shooting wars when no side controls the skies.

In contrast, smaller drones operated by land forces are, by their size and sheer number, transforming the dynamics of the lower airspace in Ukraine. That layer between where ground forces and bombers operate, referred to as the air littoral (Bremer and Grieco 2021), provides operational space for cheap loitering munitions and commercial grenade-carrying alternatives to military drones. Importantly, small drones have proven most consequential in their less sensational roles. They provide eyes in the sky and empower individual soldiers to spot enemy units and navigate artillery fire, which increases ground forces' pace and precision and keeps troops out of harm's way.

Russia's war on Ukraine has also provided a testing ground for foreign drone powers, such as Turkey, the United States, and Iran, further accelerating drone proliferation. The war has meanwhile served as a public relations campaign for armed drones and loitering munitions, changing the public image of drones along the way. Drone operations in Ukraine contrast with the use of large drone systems in the war on terror over the past two decades, which became controversial due to their association with collateral damage and targeted killings beyond official battlefields.

Changed perceptions of drone utility—especially of small armed drones and drone scouts—are likely to affect countries' future acquisitions. Indeed, the value of drone diversity in accomplishing military missions appears to be among the critical emerging technology lessons of this war. Adopting a comprehensive approach

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to drones that includes cost-efficient anti-drone defenses and uncrewed platforms across various domains will be an enduring lesson for militaries, policymakers, and industry.

Drone diversity over Ukraine

NATO classifies drones into three widely accepted main types based on their maximum take-off weight (NATO 2017): class I drones of less than 150 kilograms (kg) or about 331 pounds (lb), including small, mini, and micro drones; class II tactical drones of between 150 and 600 kg (331 and 1,323 lbs); and class III drones of greater than 600 kg. The drone dynamics in Ukraine have largely showcased class I and III systems. While large drones with missiles can be destructive under conditions of air superiority, small drones are proving crucial for battlespace awareness of infantry and maneuvering units. In addition, low-cost, one-way "kamikaze" attack drones offer yet another way to deliver explosives.

Small class I drones

From drones that fit in a backpack to model airplanes and those carrying lighter payloads (maximum 150 kg, but more commonly less than 10 kg), smaller drones have established their usefulness in Ukraine's contested airspace.

These uncrewed aerial systems have affected battlefield dynamics in two ways. First, small drones have changed the operational tempo of artillery, shortening time-critical targeting and firing cycles from about half-an-hour to three to five minutes (Watling and Reynolds 2022). Moreover, having good reconnaissance capability helps avoid wasting the limited loitering time allotted to kamikaze drones, especially when ammunition stocks are running low. Thanks to drone intelligence, blind shelling is becoming rare. Second, drone scouts provide unprecedented situational awareness down to the level of a foot soldier. Their real-time view of the battlefield enables troops to spot enemy positions and monitor adversary movements without risking the lives of human special forces (Page 2022).

In addition, most small drones have commercial origins and are easy to obtain. Both the Russian and Ukrainian armed forces continue to receive hobbyist drones in large numbers through "dronations" from their populations, including via crowdfunding campaigns. These so-called AliExpress and Amazon drones have been repurposed for spying and dropping hand grenades on targets due to their user-friendliness and low cost (hundreds or thousands, compared to millions of dollars for large drones). For instance, Chinese commercial DJI Mavic mini drones represent a key tactical reconnaissance and artillery targeting capability. However, with shorter ranges, weaker endurance, and vulnerability to jamming and spoofing, these drones are less capable than proper military-grade counterparts.

Drones are also employed for psychological warfare missions and can have non-kinetic effects. This can include propaganda, such as recording videos of ambushes and posting them on social media, as well as documenting post-battle damage and war-crimes for shaming the adversary and mobilizing the attention of the global community. Unarmed drones aid targeting other lethal systems, such as howitzers and mortars, from altitude and distance without crossing the threshold of active engagement. Noticing a small drone scout in the sky means an enemy's artillery is usually not far and can intimidate an adversary's soldiers.

Small drones have thus helped increase precision and pace of artillery fires and keep soldiers safe. Yet, these tasks are not dissimilar from those drones performed in the last century, giving them evolutionary, not revolutionary, flavor. The drones of the 1960s navigated artillery fires, acted as decoys, and performed surveillance, albeit on a much lesser scale and scope than today (Hall 2014).

Large class III drones

Early in the war in Ukraine, the Turkish military drone Bayraktar TB2 grabbed global headlines. Bayraktar acquired almost mythological significance for the Ukrainian resistance, and there were even songs composed to honor it. Ukraine bought up to two dozen of these drones prior to the war to conduct reconnaissance, aid in targeting, and carry out strikes. A Bayraktar is the size of a small airplane and provides a means to deliver firepower over long ranges (300 km) and strikes behind enemy lines at an altitude of 7 km. Some well-known examples of the military utility of the Bayraktar are the sinking of the Moskva warship and striking of the Bryansk oil depot on Russian territory (Despont, Kunertova, and Masuhr 2022).

TB2 drones had already attracted significant public attention during the second Nagorno-Karabakh war of 2020. At first glance, the use of TB2s by Azerbaijan against Armenia was very successful. However, this was only because Azerbaijan achieved air superiority early in the conflict and its drones remained outside the range of Armenian short- and medium-range air defenses (Shaikh and Rumbaugh 2020).

Russia has its own such systems, namely the Orion combat drone, though its impact has been limited at best. Moscow has only been able to produce a small number of units due to international sanctions and export controls. Additionally, Russia has never been a leader in producing indigenous drone technology and faces constraints from its industrial base that restrict the nation's capacity to manufacture armed drones (Bendett 2022).

Consequently, Russia has instead turned to Iranian drones. These systems are cheaper and rely on commercial components. The Ukrainian military has begun shooting down and capturing Iranian-supplied Mohajer-6 drones, which are like the Bayraktar TB2. Representatives from Kyiv have claimed they are inspecting the system to improve interception capabilities (Helfrich 2022).

Lethal combat operations are not the only ways these systems are contributing to the war. Large and tactical surveillance drones are useful for gathering information over extended periods of time. Russia used its Orlan-10 reconnaissance drone in this capacity, but it faced obstacles in providing good quality intelligence, mainly due to unreliability of its systems. Early in the war, Russia lost a drone over Romania just days after a Soviet-made drone crashed in Croatia (Euronews 2022). Similar accidents resulting from the use of unreliable drone technology could lead to horizontal escalation in the form of a security risk spill-over from the battlefield.

Despite their fame, large drones oftentimes lack utility for projecting airpower. These systems, typical for the first drone age during the war on terror, have long ranges, can remain deployed for lengthy periods of time (between 12 to 26 hours, with a General Atomics MQ-9 Reaper now doing so even up to 40 hours), and can execute remote strikes. When no side has air superiority, the Bayraktar and other large drones are vulnerable to air defenses and electronic countermeasures. They are also expensive to replace; one TB2 costs about $2 million. This prevents these drones from making a substantial contribution to offensive air operations (Calcara et al. 2022).

Loitering munitions

Kamikaze drones or loitering munitions are non-recoverable one-way attack drones that detonate on impact (Deveraux 2022). Situated in-between a drone and a missile in military function, they behave like disposable ammunition and offer an unambiguously offensive capability that can loiter in the target zone prior to impact. Before the war in Ukraine, loitering munitions made noticeable appearances in Libya (Turkish Kargu drone) and Nagorno-Karabakh (Israeli Harop drone).

Both Russia and Ukraine have deployed loitering munitions of comparable performance (with less than a 4 kg payload and limited to a 30 km range). While Ukraine already operated its indigenously designed and manufactured RAM II, Russia deployed its own Lancet and KUB-BLA systems. Loitering munitions were also part of the first weapon deliveries to Ukraine from the United States in March 2022. Ukrainian troops targeted the positions of Russian forces with lightweight Switchblade 300 drones. Kyiv later received American-made Phoenix Ghost and Polish-developed Warmate drones. Even with these systems' limited range and performance, they increase the vulnerability of armored vehicles and logistics operations.

Since mid-September, Ukraine has been frustrated with Iranian-supplied Shahed-136 kamikaze drones operated by Russia (Trofimov and Nissenbaum 2022). Russified as Geranium-2, these long-range loitering munitions can carry 50 kg of explosives over 2,000 km, orders of magnitude farther than Switchblade's range of 10 km. These weapons allow Russian forces to strike targets deep in Ukrainian territory and on the cheap. Essentially flying bombs, these drones are most effective against fixed sites since they lack dynamic navigation systems and use a combination of inertial guidance and commercial satellite navigation that is vulnerable to jamming.

Russia can afford to deploy large numbers of the Shahed because this system is much cheaper than regular missiles. It costs roughly $20,000 per piece versus $1 million for a single standard cruise missile. Yet, the relatively slow speed of the Shahed (185 km/hour) and the use of a vulnerable commercial navigation system has allowed the Ukrainians to intercept more than 80 percent of these incoming drones with anti-aircraft missiles, rifles, machine guns, and electromagnetic jamming (Hird et al. 2022). Regardless, the remaining 20 percent—working in concert with cruise missiles—destroyed one-third of Ukraine's electrical grid within one week. Four million Ukrainians lost power, and critical infrastructure suffered serious damage. The continued attacks with relatively cheap Shahed drones are also a drain on Ukrainian resources, exhausting Kyiv's limited stock of expensive air defense missiles.[1]

The Ukrainians have tried to develop their own long-range loitering munition with an uneven success rate. In August, they attacked Russian Navy tactical jets at Saki Airbase and the Black Sea Fleet headquarters in Sevastopol with a Chinese-built, fixed-wing drone from AliExpress (costing $8,000 per unit) repurposed into a suicide drone (Rogoway 2022). Similarly, on October 29, Ukraine launched an attack on the Sevastopol Naval Base housing Russia's Black Sea Fleet with drones and kamikaze "drone boats"—uncrewed surface vessels—filled with explosives, (Altman, Payne, and Rogoway 2022). This attack damaged at least one minesweeper and one frigate equipped with Kalibr cruise missiles. Even without inflicting massive damage on the Black Sea Fleet, the Ukrainians reduced Russian capacity to launch sea-based missiles. Perhaps the most impressive Ukrainian drone operation to date, however, has been Kyiv's use of Soviet-era Tu-141 surveillance drones to strike Engels Airbase. Hundreds of kilometers beyond Russian borders, the strikes demonstrated Ukraine's capability to gradually extend the range of its drone attacks.

Yet, calling loitering munitions a "gamechanger" would be an overstatement. The advantages they convey rely on keeping a low profile on radars and deployment in large numbers. But loitering munitions neither allow soldiers to physically capture territory, nor are they militarily efficient. Still, they depend on quality intelligence to spot suitable targets. Due to these limitations, it has quickly become clear that low-tech drones, such as those supplied by Iran, will not have a major military impact on the war (Kunertova 2022). However, when Moscow's objective appears to be spreading fear and terror, the drone attrition rate is a secondary consideration. The intention is to break down Ukrainian resistance by striking cities, civilian infrastructure, and symbols of Ukrainian nationhood and modernity (The Economist 2022).

Drones trends beyond the Ukraine war

Despite the quantity of drones deployed in the war, the number of soldiers dying on both the Russian and Ukrainian sides in firefights confirms the continued centrality of human, not machine, combat. To be fair, drones have brought about significant evolutionary changes by improving the pace and precision of artillery and providing intelligence to individual soldiers. However, the ongoing drone warfare in Ukraine is accentuating three interconnected and consequential technology trends of the so-called second drone age, defined by the global proliferation of military and commercial drone technology in which both state and non-state actors compete to control the skies (Rogers 2021).

Scale vs. sophistication

Prior to Putin's war on Ukraine, Houthi rebels attacked oil fields in Saudi Arabia with drones in 2019 (Allison and Herzog 2019). Their strikes showed that even poor-quality drones can destroy infrastructure and kill people. Cheap attack drones cannot be stopped by much more expensive air and missile defense systems like Patriot batteries (Said, Malsin, and Donati 2019). This capability mismatch epitomizes the asymmetry of armed conflicts. Similarly, in an active shooting war where no one controls the sky, drone warfare is less about technological sophistication and more about the ability to deploy in large numbers. This is especially true when armed conflicts mutate into a war of attrition, as belligerents aim to inflict increasing damage while decreasing their own costs.

The low cost of less sophisticated vehicles enables a rudimentary drone swarming tactic, or "fake swarms" (Kallenborn 2021). These are different from artificial intelligence-enabled swarms, which rely on greater levels of autonomy and are immune to jamming. The swarming doctrine relies on the drone formation's ability to communicate, coordinate, and act in a coherent way so that the adversary faces "an insuppressible collection of targets that are, seemingly, everywhere and nowhere at once" (Scharre 2014).

The massive number of drones deployed by armed forces surely presents some challenges. Militaries must enable drones to coordinate with each other, exchange high-volume data among themselves and with ground control stations, and execute missions in a networked fashion. For those defending against swarmed drones, the combination of hard and soft kill countermeasures has become crucial for effective anti-drone defenses. Whether drones are concentrated to overwhelm air defenses or dispersed to provide persistent surveillance over the operational theater, they contribute to the thickening of air traffic.

Drone proliferation and the air littoral

Drones' increased popularity and military utility manifests in congesting lower airspaces up to 3 km above the Earth's surface (Bremer and Grieco 2021). Critically, cheap small drones loaded with light explosives increase the number of actors that can contest the skies. Battles now include not only the space around ground troops, but also the space immediately above them, creating minefields in the air. The widespread use of inexpensive armed and single-use attack drones could thus make close air support and ground attack aircraft even more obsolete in conflicts with denser and capable air defenses.

The war has also produced a massive public relations campaign for foreign drone powers, which will almost inevitably lead to further drone proliferation (Feldstein 2022). Iran and Turkey are now employing drone diplomacy to chase geopolitical ambitions through armed drone sales, broadening their regional and global ties (Zanotti and Thomas 2022).

Turkey has also risen to assume the position of one of the main exporters of large armed drones worldwide (Cole

2022). Just like after the second Nagorno-Karabakh war in 2020, when the Bayraktar TB2 became an export hit, Turkey is experiencing increased demand for its drones. This is especially the case from countries that have been largely unable to purchase technology from the traditional drone powers (the United States and Israel).

The war will also elevate Iran as a more prominent drone exporter, as well as increase the presence of commercial drone components on battlefields. Russia's purchase of Iranian drones will support Tehran's armaments industry, whose primary customers up until now have been its own militias. While China is one of the largest exporters of armed drones, its military drones have not featured in the conflict yet. However, Chinese commercial parts in Iranian drones have indirectly contributed to supplying weapons to Russian forces (Albright, Burkhard, and Faragasso 2022). Many of the commodities used in the Iranian drones are off-the-shelf parts used in civil aircraft, including civilian drones. For instance, the Austrian Rotax 912 engine produced for small civil aircraft was found in the first Mohajer-6 drone downed in Ukraine. These engines were known for powering the American-made MQ-Predator drones.

Commercial drone components offer an affordable option for countries with limited resources. Accordingly, the war presents an acute test for governments' capacity to monitor the export of dual-use drone technology moving forward. Most civilian exports are handled directly by customs officers at borders who cannot truly verify the destination and end-use of exported commodities. They can only ensure the goods crossing the border correspond to the customs declaration.

In addition to regularly organizing fundraising efforts to replenish its arsenal of uncrewed vehicles, Ukraine's regional partners like Poland, Latvia, and Lithuania have also organized "drones for Ukraine" crowdfunding campaigns. Such efforts signal that the supply of drones has moved beyond centralized control by national governments through local manufacturing bases and commercial supply lines. However, adoption challenges loom in the case of cheap weaponized commercial drones with longer ranges. These systems rely on credible intelligence to strike their targets, which takes time to develop and can hinder drone proliferation and effective use (Gilli and Gilli 2016).

Stopping the drone and its operator

Some observers point to damage from Russian strikes with Iranian Shahed systems to illustrate drones' allegedly game-changing effects on warfare (Seligman 2022). Indeed, advances in range, payload, information transmission, multi-drone teaming, and precision-strike capabilities are widening the spectrum of drone threats. As the technology is developing and diffusing more rapidly than current air defense systems can cope, militaries await effective countermeasures against small drones (Kofman 2020).

Non-kinetic measures offer an alternative. For instance, Iranian-supplied drones are relatively low-tech and guided by a civilian Global Positioning System, which can be jammed. Drone jammers have a rather small operating radius (10 km at the upper end), so jammers would essentially have to be spread out across the entire war theater to mount an effective drone defense. In addition, jamming equipment alone will not reliably counter the threat of low-cost, potentially autonomous loitering munitions and small drones.

Still, NATO member countries have agreed to provide Ukraine with hundreds of drone jammers to neutralize intensifying Russian drone attacks (NATO 2022). They also promised new air defenses, like the American NASAMS and German IRIS-T SLM systems, to protect Ukraine's cities and critical infrastructure against missiles. The efficacy of these air defenses against slow and low-flying loitering munition drones remains a "known unknown." Furthermore, it is just too expensive to use missile interceptors costing millions of dollars to shoot down cheap drones.

The challenge of anti-drone defense therefore combines the need for both militarily reliable and cost-effective countermeasures, so that the defenses are cheaper than their targets. One potential option includes combining anti-aircraft guns with compact radar and laser systems for detection and ranging (Bronk, Reynolds, and Watling 2022).

The war in Ukraine has also opened a new venue for innovation in the development and deployment of uncrewed platforms that will have implications for anti-drone defenses. Drone boats carrying explosives and deployed in tandem with aerial drones surprised and even overwhelmed Russian defense systems in Sevastopol Bay in October 2022. Similarly, in April, just two months into the war, Ukrainian forces sank the Moskva cruiser, the flagship of the Russian Black Sea Fleet. This operation saw Bayraktar TB2 drones deflect Russia's air defense systems, giving Kyiv's Neptune anti-ship missiles a clear path to their target.

Naval drones employed alongside aerial military and commercial militarized drones cannot only act as decoys to distract the defenses, but they may also eventually serve as reconnaissance and target acquisition platforms. Further innovative uses of drones may herald the proliferation of land, air, sea, and underwater drones, expanding drone threats into all domains of operations, and introducing a third drone age defined by full-spectrum drone warfare (Rogers and Kunertova 2022).

Droning ahead

Although drones alone are hardly a decisive war-winning capability, Russia's war on Ukraine has resulted in high public visibility of bomb-dropping drones, large and small, and the near invisibility of drones' enabling functions. This contrasts with two decades of deploying large drones for long endurance missions as part of counterterrorism operations. The popularity of low-cost kamikaze drones also reinforces the trend of understanding drones as disposable ammunition. It contributes to the changing image of an armed drone—from missile launchers two decades ago to today's bomb-dropping quadcopters and lightweight suicide drones (Gettinger 2022).

The war is accordingly accelerating drone proliferation both horizontally and vertically. Horizontally, the import of foreign drones to the battlefield points to the rise of Turkey and Iran as the new drone powers. Vertically, the availability of smaller and cheaper systems diffuses drones down to the individual soldier at the platoon level. Meanwhile, loitering munitions are further confirming the utility of drones in lethal military missions, albeit as ammunition and not as platforms. Yet, the ability to target forces beyond the battlefield is highly dependent on the quality of intelligence and communication links. The longer the range, the more demanding targeting support it requires. In addition, mastering a new weapon requires not only technological know-how but also the ability to integrate such systems into warfighting concepts.

On the flipside, the war in Ukraine confirms that drones are becoming stealthier, speedier, smaller, more lethal and easily operable, and available to more actors. Stopping them is looking increasingly challenging for the United States and its European allies, especially due to the broad stagnation of air defenses resulting from decades of fighting insurgents and weaker state opponents.

The United States' 2022 Missile Defense Review mentioned drone threats for the first time. To combat such threats, reliable anti-drone defense will need to be cost-effective, denser, and more robust, requiring layered and integrated air and missile defense systems that also include non-kinetic and soft-kill technologies. A comprehensive approach to drones also needs to prioritize effective countermeasures against small drones to address the congesting air littoral. Low tech and low-flying drones further reveal that while musing about AI-enabled swarms, militaries still wait for effective defenses against existing drones.

Large armed drones are being superseded by a widening spectrum of lethal drones. While expensive capability development projects for large drones often have few beneficial outcomes (Kunertova 2021), less advanced drones can produce similar effects for a fraction of the costs. Changing public perceptions are also making the use of armed drones more politically acceptable. Even Germany, which had been embroiled in a "to arm or not to arm" drone debate, has learned lessons from the war and decided to weaponize its Israeli Heron drones (Jennings 2022). Once decried as flying assassination robots conducting strikes and ethically dubious executions in the 2000s to 2010s, drones have now become an unavoidable part of interstate conventional warfare.

These trends will further complicate the export control of drone technology. Armed drones are defined as missile technology under the guidelines of the Missile Technology Control Regime (MTCR). But only larger drones with a range of at least 300 km and carrying explosives weighing at least 500 kg are subject to such restrictions (Kimball 2020). However, most armed drones used in the war in Ukraine fly right under the MTCR's radar. The loitering munitions seen on the battlefield in Ukraine are smaller than a cruise missile, can carry three or more times the explosive payload of an artillery shell, and use commercially available engines. Efforts to control the export of armed drones thus lag considerably behind the realities on the battlefield. In addition, local drone manufacturing workshops will make monitoring and controlling arms exports increasingly difficult (Dass 2022).

To make matters even more complex, as in other security domains (Bollfrass and Herzog 2022; Willett 2022), the war in Ukraine is quickly bringing future trends for drone use into view. Soldiers in tomorrow's wars will encounter not only uncrewed long-range persistent eyes in the sky and robotic missile launchers, but also a new generation of small, stealthy drone scouts across most domains of operation. Just like the scenes from Bakhmut and Kyiv at the end of 2022 showed, drones can indeed play different games.

Note

1. Based on the latest evidence, some recent analyses note that due to the lack of loitering to hunt for a target, Shaheds behave more like cruise missiles, albeit propeller-driven ones, than like drones (see, e.g., Rubin 2023).

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