CHAPTER THREE

# The Uninhabited War in Ukraine

The *Leleka* light UAV is employed by Ukrainian forces in the ISR role
Photo by Viacheslav Madiievskyi/Ukrinform/NurPhoto via Getty Images

When Russia launched its full-scale invasion of Ukraine in 2022, both belligerents were operating uninhabited aerial vehicles (UAVs) in a broadly traditional manner, utilising limited inventories of medium-altitude long-endurance (MALE) systems and smaller tactical systems. Three years later, in what has become an attritional fight, the use and nature of the UAVs employed have transformed in both role and volume. What remains in question is whether UAV use in Russia's war of aggression in Ukraine will remain *sui generis*, or the extent to which this conflict prefigures what may come.

Ukraine had fewer than 100 UAVs in its inventory on 24 February 2022. In contrast, it aimed to produce 4.5 million in 2025, with Russian targets only marginally lower.[1] From their traditional roles as intelligence, surveillance and reconnaissance (ISR) enablers and niche air-to-surface weapon delivery platforms, UAVs have become the most lethal type of system in the war. By 2025, they had surpassed artillery as the leading cause of front-line casualties, accounting for up to 80% of losses.[2]

The steep rise in UAV numbers used in Ukraine has, furthermore, provided an alternative, non-traditional approach to ISR collection. The extraordinary number – in the thousands – of small and mini-UAVs being operated concurrently provides voluminous data contributing to arguably an unprecedented level of situational awareness for both Russia and Ukraine. The small- and mini-UAV capacity to collect data in Ukraine is the gift of their sheer number: their individual ISR footprint is constrained only by their payload and performance limitations.

This approach has required the development of new command-and-control (C2) tools capable of processing, integrating and exploiting this data in near-real time. This, when combined with UAV-delivered ordnance, reflects elements of what was once dubbed network-centric warfare. Ukraine has, in effect, used uninhabited systems to create a tactical reconnaissance-strike complex, which is proving effective on the battlefield.

## Initial stages

Both Russia and Ukraine had employed UAVs for ISR and limited ground-attack purposes in the period between Moscow's illegal annexation of Crimea in 2014 and the full-scale Russian invasion eight years later. While the scale of UAV use during this period remained limited, particularly on the Ukrainian side, these

## KEY TAKEAWAYS

### OPERATIONAL ENVIRONMENT

Ukraine has provided a combat incubator for the operational development of uninhabited aerial vehicles (UAVs), with new classes of such vehicles emerging. First-person view and one-way attack UAVs have become ubiquitous in the war.

### DANGER CLOSE

The present generation of medium-altitude long-endurance UAVs has been shown to be vulnerable when operated within range of ground-based air defence. The extent to which this threat can be mitigated remains to be seen.

### WIRELESS PROBLEMS

Radio frequency (RF) off-board links, irrespective of the class of UAV, are a potential vulnerability in a contested electromagnetic environment, making jamming-resistant RF links more essential.

### OBJECT LESSONS

Russia's war of aggression in Ukraine offers lessons for the uninhabited-systems realm, but the extent to which it more broadly represents a template for UAV use is debatable.

efforts laid the groundwork for developments to come. They served as early points of departure for many of the capabilities and operational practices that would later become central to the war.

Although now largely overlooked, the pre-2022 conflict in the Donbas also featured a significant third-party UAV operator in the form of the Organization for Security and Co-operation in Europe (OSCE) Special Monitoring Mission to Ukraine. Between 2014 and 2021, this OSCE mission conducted over 13,000 UAV flights, using the Schiebel *Camcopter* S-100 rotary-wing system and commercially available quadcopters to monitor the ceasefire. UAV-derived intelligence played a central role in the mission, with 58% of the observed violations that involved heavy weapons detected by uninhabited platforms. The UAVs also provided high-quality imagery that improved analytical confidence and increased public awareness of the mission's findings. Additionally, UAVs enabled intelligence gathering in hazardous or inaccessible areas, extending operational reach while reducing risk to personnel. The contested nature of the environment was evident in the frequency of interference, with the mission's UAVs reportedly jammed more than 1,600 times and fired upon on approximately 200 occasions.[3]

Electronic warfare (EW) has been a constant factor over the past decade and has been increasingly prevalent in the wake of Russia's full-scale invasion. Following the annexation of Crimea, by 2015 Russia had already deployed in Ukraine EW systems capable of global positioning system (GPS) jamming.[4] These posed a challenge to Western UAVs, many of which had been designed for counter-insurgency operations and lacked resilience against high-end jamming environments. Ukrainian forces praised the RQ-11B *Raven* for its high-quality sensors but found it nearly unusable near the front line due to its limited resistance to electronic interference.[5]

Whereas current UAV operations in Ukraine are dominated by small and mini-UAVs, Ukraine's MALE UAVs played a notable role during the opening stages of the war. Ukraine appears to have acquired at least 20 Turkish Baykar *Bayraktar* TB2 MALE UAVs for its navy and air force before the conflict. Shortly after Russia's full-scale invasion, Kyiv took further deliveries of TB2s, with then-defence minister Oleksii Reznikov suggesting it might have received as many as 50 more in the first few months of the war.[6]

Russia began its campaign with few forward-deployed ground-based air defence (GBAD) or EW capabilities, operating under the flawed assumption that there would be little Ukrainian resistance to its attack. Consequently, even the potentially vulnerable TB2s could be operated by Ukrainian forces at short range against ground targets. Russian air defences proved so ineffective initially that not only were TB2s not intercepted, they were used to attack Russian surface-to-air missile systems.[7] Ukraine also made use of the TB2's potential for naval operations, targeting several Russian patrol boats.[8]

Beyond its immediate military utility, the TB2 also became a useful propaganda tool. Ukraine capitalised on high-resolution strike footage captured by the TB2's Wescam sensors, releasing these videos to the public.[9] This tactic not only highlighted Ukraine's defiance but also helped sustain domestic morale.

However, following the failure to secure a quick victory and the ensuing disarray, Russian forces succeeded in consolidating their air-defence and EW systems, heightening considerably the threat to TB2 operations. Open-source data suggests that Russian forces downed at least 16 TB2s between March 2022 and April 2023.[10] This resulted in Ukraine gradually withdrawing it from front-line combat roles, with Ukrainian officials acknowledging the platform's diminished utility. In response to the growing threat, TB2 employment was revised. TB2s began to be used for stand-off ISR since, under favourable atmospheric conditions, the TB2's electro-optical and infrared sensors allowed it to operate up to 50 kilometres behind the front line, well beyond the reach of Russian short-range air defence.[11]

In addition to Turkish MALE UAVs, Ukraine sought to acquire General Atomics MQ-1C *Gray Eagle* UAVs as early as April 2022.[12] The United States government declined these requests. There were suggestions that the US decision was influenced by concerns that the UAVs might be used to strike targets within Russian territory, potentially leading to further escalation. Additionally, there were fears that some sensitive technologies could fall into Russian hands, risking technological exploitation by an adversary.[13]

Russia, for its part, entered the war with a small arsenal of domestically developed Kronstadt *Inokhodets* MALE UAVs. Designed first as an ISR asset but later armed, the *Inokhodets* had previously been used in Syria. Russia's *Inokhodets* was complemented by a small number of Iranian-made *Mohajer* 6 UAVs equipped with *Ghaem* glide bombs.[14]

Although Russia had fallen behind leaders like Israel, Turkiye and the US in UAV development, it did launch the war with a more established industry than Ukraine. Israeli technology transfers, agreed upon in 2010, had enabled the production of a local version of Israel Aerospace Industries' *Searcher* Mk II tactical UAV, known in Russian service as the *Forpost*.[15] In parallel, Russia had developed the Special Technology Center *Orlan*-10 tactical fixed-wing UAV, which entered widespread use alongside a range of smaller ISR platforms. Both the *Orlan*-10 and the *Forpost* were employed during the pre-2022 conflict in the Donbas primarily for artillery spotting and target acquisition.[16] While Russia was also experimenting with armed MALE UAVs such as the *Inokhodets* and loitering munitions, including the ZALA *Lancet* (testing these systems in Syria), Russian and separatist small-UAV activity in Ukraine during this pre-2022 period remained focused on ISR roles, with only limited evidence of armed quadcopter use.[17]

Much like Ukraine's experience with the *Bayraktar* TB2 UAVs, Russia's *Inokhodets* and *Mojaher* 6 proved vulnerable to Ukrainian air defence. Subsequently, neither has been employed over or near the front line for the most part.[18] Moscow, however, did press the TB2 and the *Inokhodets* back into front-line service during Ukraine's incursion into Russia's Kursk *oblast* in 2024. Several, unsurprisingly, were lost.[19] The rationale for the Russian use is not known, although some Russia-based commentators suggested that Ukrainian air defence in the area was weak enough to allow for the *Inokhodets* deployment. Conversely, some Ukrainian observers saw the move as one of necessity as Russia attempted to slow the Ukrainian advance, even at the cost of UAV losses.[20]

## Small advantage

Relatively early in the conflict, Ukraine began to supplement its MALE UAVs with far less expensive small and mini-UAVs. These were acquired by regular military formations, often through irregular channels, as well as by newly established specialist units, like the Aerorozvidka group, formed in 2014.[21] The primary focus of these UAV operations was ISR along the largely static front line, with artillery spotting emerging as a core mission. Ukrainian forces and Russian-backed separatists, over time, also began to modify commercial UAVs to carry small munitions, marking the beginning of improvised air-to-surface attack in the war.[22]

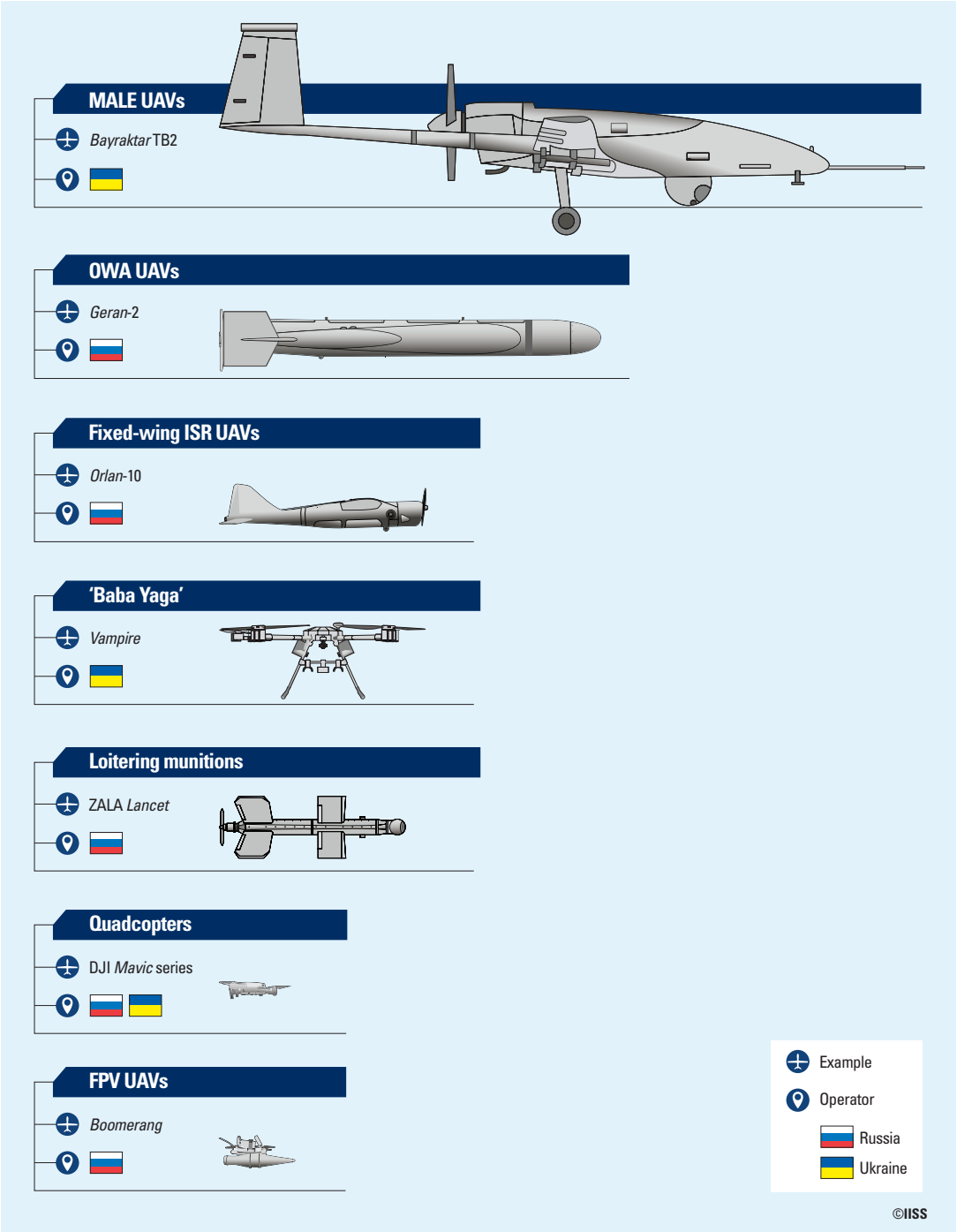
Most small UAVs in Ukrainian service were commercially available, such as the DJI *Mavic* family, and were often bought directly by individual commanders or by units using their own funds. Even before 2022, however, Ukraine had begun to leverage its large and technically skilled workforce to foster a growing number of small- and mini-UAV-focused companies. The innovative but fragmented and horizontally structured character of the industry, which continues to define Ukraine's UAV sector, was already evident.[23]

Several private Ukrainian firms developed lightweight fixed-wing ISR platforms such as the DeViRo *Leleka* and the Athlon Avia *Furia*, both of which remain in operational use. Larger state-owned defence enterprises, including the Luch Design Bureau and Antonov, in contrast, presented concepts for MALE UAVs, but none advanced beyond the design phase.[24]

Ukraine's state-led UAV development and procurement efforts were initially modest but gradually expanded in the years preceding the full-scale war. In 2016, the US provided 72 *Raven* systems to Ukraine as part of a non-lethal-assistance package.[25] Beginning in 2018, Ukraine ordered TB2s, with the first deliveries commencing in 2019 and additional batches being acquired shortly thereafter.[26] The TB2s were deployed by both the Ukrainian Air Force and the Ukrainian Navy, the latter indicating an early interest in using MALE UAVs in naval operations and using them as ISR platforms in conjunction with ground-based anti-ship missile systems.[27] In October 2021, Ukrainian TB2s went into action for the first time, striking a separatist artillery position in the Donbas.[28]

At least as significant, Ukraine also moved quickly to integrate UAV-based ISR into a flexible tactical battle management system. In 2016, the Aerorozvidka group initiated the development of

**Figure 3.1:** Selected UAV classes operated by Russia or Ukraine




**ISR** = intelligence, surveillance and reconnaissance; **FPV** = first-person view; **MALE** = medium-altitude long-endurance; **OWA** = one-way attack; **UAV** = uninhabited aerial vehicle
Note: Illustrations approximately to scale.
Source: IISS research

the *Delta* system, which sought to fuse multiple ISR sources, including UAVs, fixed CCTV installations and satellite imagery, into a real-time digital map.[29] The aim was to provide comprehensive situational awareness to both rear-area commanders and front-line units. Development of the system reportedly received support from NATO, and small-scale testing began in 2017.[30]

## Personal view

The war has become synonymous with the use of first-person view (FPV) UAVs, by far the most numerous on the battlefield. This concept emerged from commercial racing drones, and they are comparatively fast and manoeuvrable rotary-wing platforms equipped with a fixed forward-facing

A UAV operator of the 42nd Mechanized Brigade's Aerial Reconnaissance Unit in Lyptsi village, Kharkiv *oblast*, Ukraine, 19 May 2024

Photo by Yan Dobronosov/ Global Images Ukraine via Getty Images

camera that provides the operator with a real-time line-of-sight image. These systems are typically fitted with small, adapted or purpose-designed warheads and are manually guided to the target.

While more challenging to operate than standard quadcopters, FPV UAVs still require relatively limited training when compared to traditional, larger UAVs. They also have low personnel requirements, being typically operated by a small crew consisting of a pilot, a navigator and a munitions handler. Assembled locally from cheap, commercially available components, standard FPVs generally cost no more than a few hundred dollars each. In Ukraine, annual FPV production reportedly increased from 600,000 units in 2023 to 2.2m in 2024, with further growth in 2025.[31]

Ukraine and Russia are not only scaling up FPV production capacity but also working on increasing their survivability and quality. This has included the introduction of fibre-optic cable-guided FPV UAVs. Although less manoeuvrable and more vulnerable to physical obstacles than FPVs that use radio links, they are immune to electromagnetic jamming and can transmit high-resolution video until the point of impact.[32] While Ukraine initially showed limited interest in this guidance method, Russia has adopted it at scale, reportedly resulting in significant Ukrainian materiel losses, including during the incursion into Kursk *oblast*.[33]

## One-way journey

While small UAVs, including FPVs, multicopters and fixed-wing ISR UAVs, have most visibly influenced Ukraine's battlefield at the tactical level, the widespread use of one-way attack (OWA) systems has also had an impact. Only months after February 2022, Russia began acquiring and using the Iranian *Shahed* 131 and *Shahed* 136 long-range OWA UAVs. This purchase was soon followed by an effort to establish local production of the *Shahed* 136 under the designation *Geran*-2. Since then, Moscow has committed substantial resources to scaling up domestic production. It expanded its original *Geran* production facility in Yelabuga and has established a second line in Izhevsk.[34] These efforts have gradually reduced dependency on Iranian-supplied components. By mid-2025, Russia may have been producing as many as 170 *Geran*-class UAVs per day, enabling strike and decoy waves encompassing hundreds of UAVs.[35]

Moscow has continued to refine its OWA-UAV tactics, techniques and procedures. These have included varying flight speeds and altitudes, coordinated simultaneous approaches from multiple directions and, most notably, integrating UAVs with land-attack cruise missiles in combined strikes.[36] Russia is also making greater use of low-cost decoy UAVs, such as the *Gerbera*

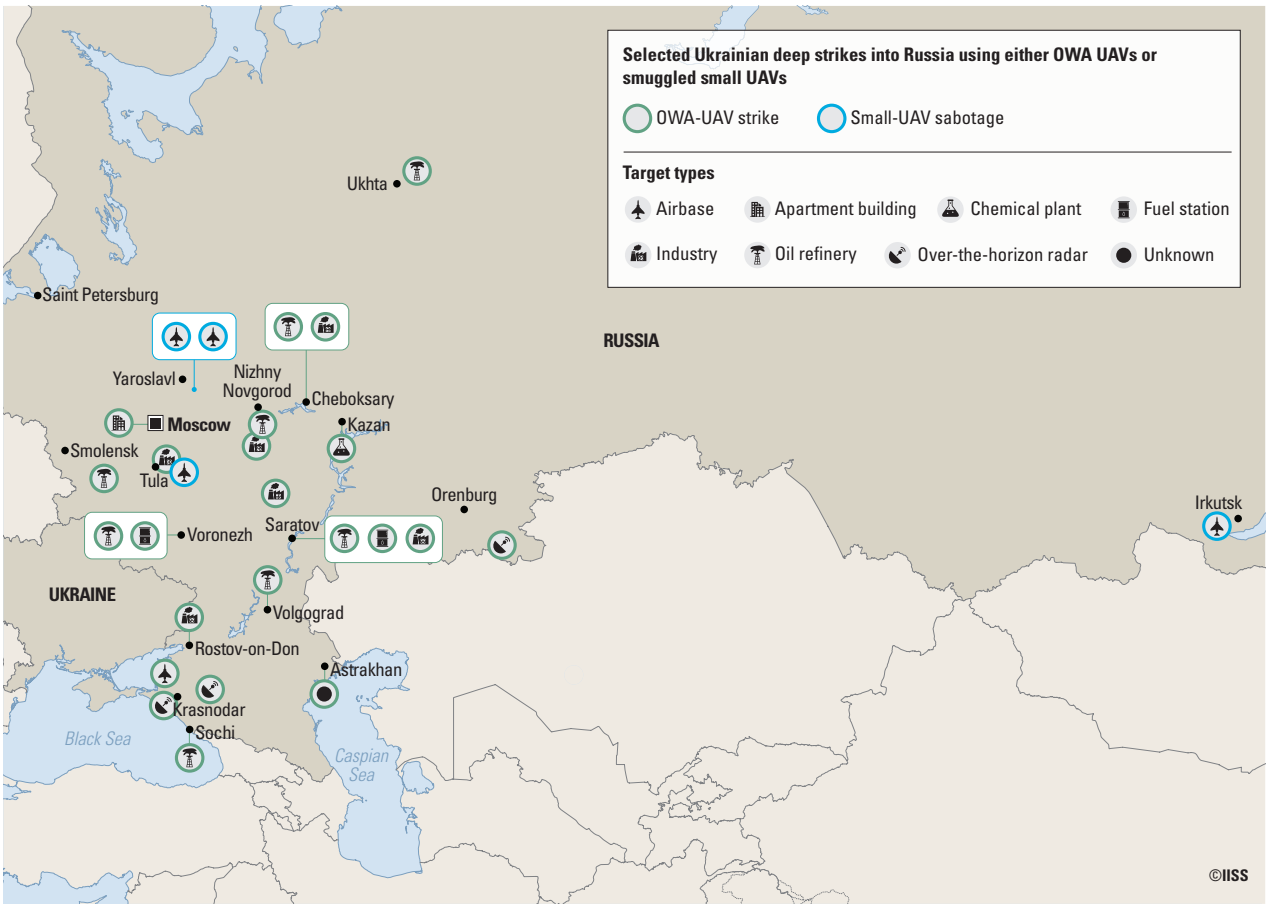
or *Parodiya*, which in some cases appear to constitute more than half of the UAVs deployed in long-range strike waves.[37] Russia appears to be increasingly employing *Geran* UAVs in tactical and operational-level strikes.[38] Video evidence suggests that, in at least some cases, these UAVs are equipped with onboard cameras and radio links for direct operator control.[39]

Ukraine, for its part, began converting commercially sourced fixed-wing UAVs such as the Chinese-made *Mugin*-5 into OWA platforms within the first months of the war.[40] Since then, these have been augmented by foreign-built systems, such as the US-made AEVEX *Disruptor*, and the YIHA-III and *Dart* 250, manufactured in Turkiye and the United Kingdom, respectively. At the same time, Ukrainian companies have made significant efforts to develop their own long-range OWA systems such as the UJ-26 *Bober*, the Destinus *Lord*, the Terminal Autonomy AQ 400 *Scythe* and the Antonov An-196 *Lyutyy*.[41] Ukraine has also developed ultra-long-range UAVs by converting light sports aircraft into OWA UAVs. Examples include the A22 *Foxbat* and the Skyranger *Nynja*, with some of these systems reaching ranges of up to 3,000 km and being used against targets deep inside Russia, such as the Russian *Geran* factory in Yelabuga.[42]

Ukraine is also operating turbojet-powered systems that further blur the line between cruise missiles and OWA UAVs. Examples include the already in service *Palianytsia*, *Peklo* and the Destinus *Ruta*.[43] Russia is also experimenting with jet-powered variants of the *Geran*.[44] These systems offer improved speed and survivability but entail trade-offs, including reduced range and higher engine costs.

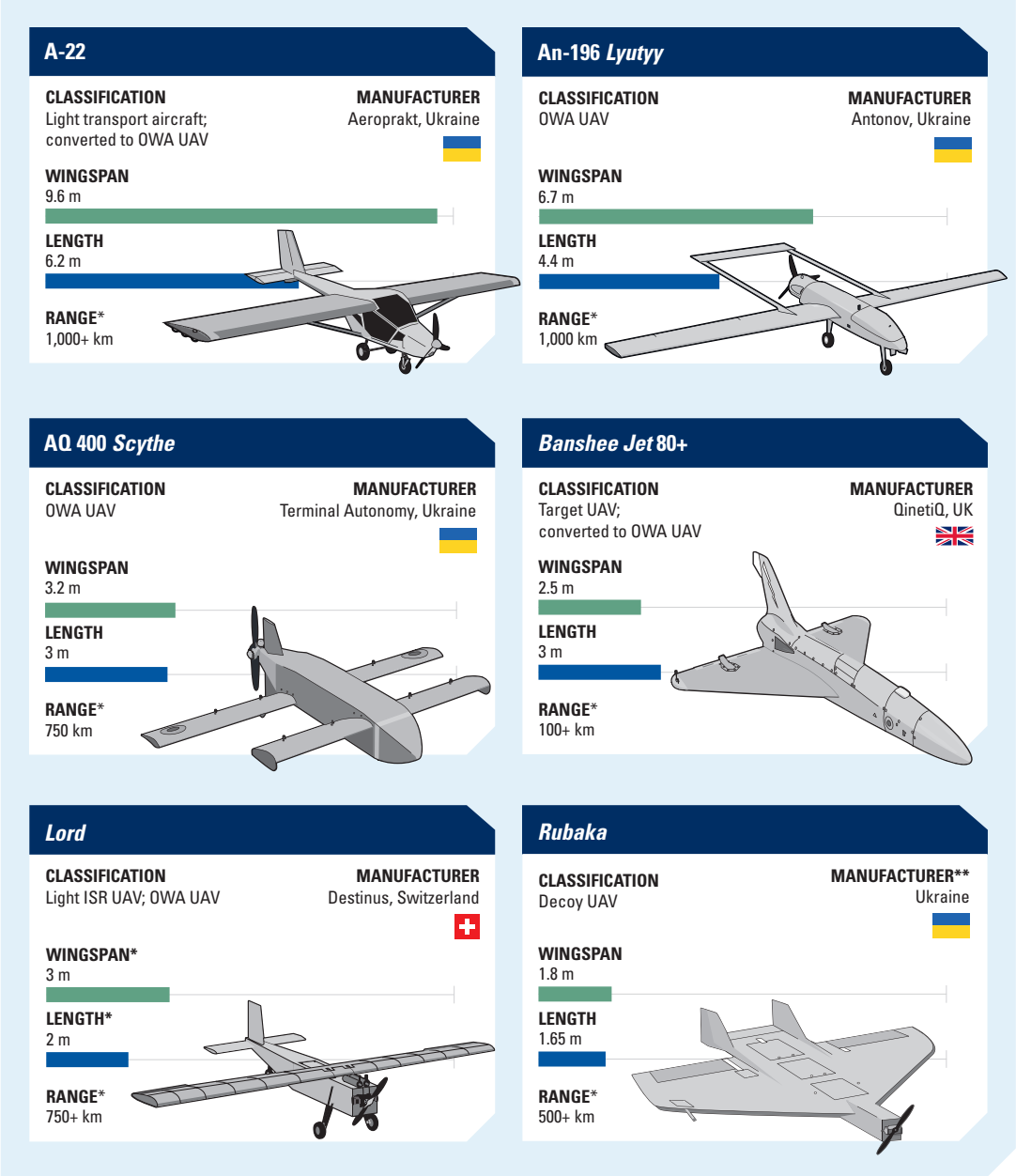
UAVs were employed at the start of the war to provide tactical ISR, collecting targeting information for weapons. OWA UAV missions reverse this relationship, with the UAV no longer serving as the collector but rather as the delivery mechanism. The use of OWA UAVs in Ukraine also requires extensive ISR to support

**Map 3.1:** Selected Ukrainian UAV deep strikes into Russia, 2025




**OWA** = one-way attack; **UAV** = uninhabited aerial vehicle
Source: IISS research

**Figure 3.2:** Ukraine: selected OWA-UAV inventory




*Estimated. **Exact manufacturer not confirmed.
**ISR** = intelligence, surveillance and reconnaissance; **OWA** = one-way attack; **UAV** = uninhabited aerial vehicle
Sources: IISS research; Military Balance+, milbalplus.iiss.org

an attack. The reason, in part, lies in the complexity of mission planning. Long-range systems such as the *Lyutyy* or *Foxbat* are not particularly survivable. Instead they are dependent on carefully designed flight paths and countermeasures to penetrate Russia's layered air-defence and EW systems. These routes rely on detailed, near-real-time intelligence about the location and status of enemy defence. The challenge increases further when the intended targets are relocatable or mobile. Ukrainian OWA UAV operators, as a result, remain in close contact with intelligence teams and continue to receive near-real-time ISR updates until the moment of launch.[45]

## Loitering munitions

Loitering munitions have been employed since the outset of the conflict. Russia's *Lancet* was already in service, while Ukraine rapidly acquired foreign systems, including the Polish WB Group *Warmate* and the US-made AeroVironment *Switchblade* 300.

Since then, Ukraine has also made progress in the local development of such systems, for instance, the RAM II and the RAM-2X. Russia's *Lancet* has demonstrated reasonable battlefield effectiveness, particularly against artillery systems.[46] Thus, Russia has expanded production and is steadily improving the system's capabilities.[47]

The use of loitering munitions has increased, with up to 7,000 *Lancet*s employed by Russian forces as of November 2024.[48] The figure, however, remains well below the volume of FPV UAVs used in the conflict. The disparity is likely due to the limited number of manufacturers and the higher unit cost of loitering munitions. A *Lancet* is estimated to cost approximately USD35,000, and a *Switchblade* around USD53,000, compared to a few hundred dollars for an FPV UAV.[49]

Originally designed to loiter over the battlefield and wait for targets to appear, in practice they are too scarce and expensive to be used in this way in Ukraine. They are instead typically cued by a separate ISR platform and launched only once a target has been identified. Their onboard sensors and loitering capacity are then used to guide them to the pre-identified target rather than to acquire new targets.[50]

Ukraine and Russia are seeking to develop cheaper and simpler variants of loitering munitions, sometimes referred to as fixed-wing FPV UAVs. An example is Russia's *Molniya* UAV, a rudimentary system constructed from aluminium tubing and plywood, incorporating low-cost, commercially available components and operated in a manner similar to an FPV UAV.[51] Ukraine's Terminal Autonomy is pursuing a similar approach with the AQ100 *Bayonet*, which has a reported unit cost of only about USD2,000.[52]

## Autonomous activity

Swarms of autonomous UAVs may remain an ambition, but it is evident from the war that greater automation is a growing feature of uninhabited-system operations. One such element widely employed by both Russian and Ukrainian forces is the automated target-acquisition system, also known as an automated target lock. This allows an operator to designate a target, after which the UAV completes the approach independent of any further command input. The main benefit is the ability to maintain accuracy even if communication links are lost during the terminal phase, which can occur at low altitude due to ground interference or short-range jamming.[53] While optical target lock has existed for decades, in the likes of the Raytheon AGM-65 *Maverick*, improvements in software and miniaturised hardware have made similar capabilities viable for small, low-cost UAVs.

More advanced automatic target recognition (ATR) has reportedly also been adopted by Ukraine using a system called *Avengers*, integrated with the *Delta* situational-awareness platform. *Avengers* is said to be capable of identifying up to 70% of enemy vehicles and equipment in video feeds.[54] The inclusion of ATR on a UAV would offer increased independence from a human operator. However, multiple challenges, technical and ethical, remain.

The integration of ATR directly into UAVs could enable fully autonomous strike operations. More advanced levels of automation, however, require greater onboard computing power and more expensive hardware. There also remain concerns over the delegation of lethal decision-making to machines. Ukrainian officials have said the country remains committed to maintaining human control over such decisions, either through human-in-the-loop mechanisms or by restricting autonomous engagements to predefined geographic areas. In the context of the Russia–Ukraine war, where both sides often employ similar types of equipment, fully autonomous targeting systems would also carry a heightened risk of fratricide.[55]

The extent to which ATR has already been adopted by Russian or Ukrainian UAVs is difficult to determine. Operational security constraints, the inherent challenge of inferring software capabilities from battlefield debris, and the broad application of the term 'artificial intelligence' to relatively simple automated functions, such as target locks, all obscure the picture. Nevertheless, certain indicators suggest that relevant capabilities may be emerging. Russia's V2U loitering munition, first documented in 2025, was found to contain a Jetson *Orin* Nano Developer Kit.[56] This advanced edge-computing module is optimised for artificial-intelligence and machine-learning applications and could support either ATR, visual navigation in global navigation satellite system (GNSS)-denied environments, or both. In the same year, a Jetson *Orin* unit was also identified in an experimental *Shahed* variant equipped with

electro-optical sensors and reportedly delivered from Iran.[57] On the Ukrainian side, there have been claims that the *GOGOL*-M FPV mothership is capable of autonomous target identification and engagement, although confirmed technical details remain limited.[58]

Ukrainian officials have emphasised that autonomous swarms are unlikely to be realised soon given ongoing software and hardware challenges.[59] Nevertheless, there are indications that some of the elements required for swarming might already be emerging on the battlefields of Ukraine. Both Russian *Geran*-2 OWA UAVs and *Gerbera* decoy UAVs have reportedly been equipped with Chinese-made mesh network modems, which could allow them to act as repeaters and also enable communications among multiple UAVs.[60] Additional indications of Russian efforts to enable limited collaborative behaviour have emerged in relation to the V2U loitering munition. In one incident, multiple V2U UAVs reportedly entered a circular loitering pattern prior to engaging their target. Imagery of debris of V2Us involved in the attack showed distinctive, brightly coloured wing markings. These visual identifiers may have been intended to facilitate optical deconfliction or relative positional awareness among UAVs operating in close proximity, potentially enabling rudimentary coordination.[61]

## Integrating ISR

*Delta* has become a central element of Ukraine's C2 architecture and has undergone considerable development since its introduction. The platform now includes a near-real-time digital map displaying the positions of enemy and friendly forces, a secure messaging service and a video-streaming feature known as *DeltaTube*, which provides live feeds from ISR UAVs and fixed cameras. In addition to data from UAVs and front-line observers, *Delta* also incorporates ISR from a broad range of other sources. These include satellite imagery, inputs from supporting foreign governments and vetted reports from the Ukrainian civilian population.[62] The system's modular architecture allows for new features to be integrated quickly, while its cloud-based and platform-agnostic nature enables users to access it from a variety of devices, including standard web browsers. In combination with resilient, high-bandwidth and low-latency satellite internet services, such as *Starlink*, this allows for operational flexibility.[63] Another feature of *Delta* is that it also makes a higher level of situational awareness available to lower ranks, thereby supporting faster and more decentralised decision-making.

Traditionally, control of small UAVs has relied on a direct line-of-sight radio link, with only larger MALE UAVs equipped for beyond-line-of-sight

A Ukrainian soldier readying an Airlogix fixed-wing ISR UAV for launch outside Kyiv, 9 November 2022

Photo by Paula Bronstein via Getty Images

(BLOS) satellite communications (SATCOM). Both Ukrainian and Russian innovations, as well as wider technological advances, however, are enabling new types of BLOS communications that are viable for smaller platforms. One approach employed by both sides involved the use of airborne relays mounted on UAVs maintained within line of sight of a ground control station and another UAV, effectively repeating the signal. This allows loitering munitions and FPV drones to maintain stable control links even at very low altitudes, where ground clutter would otherwise degrade signal quality, thereby improving accuracy by reducing the risk of link loss before impact. It also extends the effective communications range of these systems. Both sides have further developed fixed-wing UAVs that function as FPV launch platforms and as airborne relays. This increases the communications and the effective range of the FPVs.[64]

Technological advances in satellite communications and satellite internet technology have also enabled their wider application in UAVs. Previously, high-bandwidth SATCOM for BLOS was only available to large MALE UAVs due to limitations posed by antenna size as well as satellite capacity. Now, low Earth orbit (LEO) constellations, using beamforming technology like *Starlink*, provide affordable, high-bandwidth and low-latency connections via relatively compact terminals. This enables not only their widespread use for C2 and communication among UAV units, including through internet-based situational-awareness platforms like *Delta*, but also the integration of SATCOM capabilities into much smaller uninhabited systems.

Ukraine has mounted *Starlink* terminals on heavy multicopter UAVs such as the *Nemesis*, allowing for their operational range to be limited by battery life rather than line-of-sight communications range.[65] Russian forces, in turn, have experimented with installing *Starlink* on fixed-wing UAVs. At least one such modification was observed on a *Shahed*, although the modification does not appear to have been widely adopted.[66] While the use of compact SATCOM systems on aerial vehicles remains limited, these systems have already become essential to the operations of Ukrainian uninhabited surface vessels. As the size, cost and power consumption of LEO SATCOM continue to decrease, further integration into UAV operations is only expected to accelerate.

Both Russian and Ukrainian UAVs have made use of civilian long-term evolution and 3G cellular infrastructure within enemy territory. Open-source reporting indicates that OWA UAVs have been equipped with cellular modems and SIM cards, enabling them to access local networks.[67] The extent to which this practice has been adopted, as well as the role cellular connectivity plays in navigation, remains unknown. It is unclear whether the mobile networks are used only for rough geolocation through the pinging of cell-phone towers, low-bandwidth transfers of basic telemetry data or more advanced datalinks that could support video feeds.

## War in the electromagnetic spectrum

With UAVs now representing the single largest source of casualties, and Russia's armed forces having maintained a long-standing focus on EW, it is unsurprising that Ukraine has arguably become the most heavily contested electromagnetic environment in the world. Measures undertaken by Kyiv and Moscow to disrupt adversary UAV and other operations include jamming and spoofing of GNSS, as well as jamming UAV datalinks.

Navigation services such as GPS are often effectively unavailable near the front line. As a result, even advanced Western precision-guided weapons that rely on GPS, including the version of the Ground Launched Small Diameter Bomb initially delivered to Ukraine, have proven largely ineffective in contested areas. The same issue was reported with several Western UAV designs delivered to Ukraine.[68] In its efforts to harden UAVs against GNSS jamming and spoofing, Russia has made extensive use of controlled reception pattern antennas (CRPAs). These use multiple antenna elements to identify the direction of interfering signals and filter them out, helping UAVs maintain access to satellite navigation. Initially, Russian *Shahed*-type UAVs used Iranian-made four-element *Nasir* CRPA modules, which were later replaced by the Russian-made four-element *Kometa* module. While jamming these systems is difficult, Ukraine appears to have made some progress. This is evidenced by reports of *Shahed*s being spoofed, crossing back into Russia or losing signal, as well as by Russian modifications to *Shahed*s that now include more capable Chinese-made 16-element CRPAs.[69]

Attendees at an exhibition of Ukrainian company Kvertus's electronic-warfare systems in Lviv *oblast*, 28 May 2024

Photo by Yury Dyachyshyn/ AFP via Getty Images

Another approach to navigating in GNSS-denied environments involves the use of non-GNSS systems, particularly visual navigation systems. These compare inputs from electro-optical sensors with stored reference imagery to estimate the UAV's position. While similar navigation modes, such as Digital Scene Matching Area Correlation, have been used for cruise-missile guidance for decades, recent advances in hardware and software have made the development and deployment of such systems significantly easier. This, in turn, has enabled more widespread use on smaller, low-cost platforms. Currently, these systems face challenges, including uncertainties introduced by terrain changes and difficulties associated with low-level flights. Work to overcome these issues is undoubtedly ongoing, given the value of being able to operate in a GNSS-denied environment.

In addition to GNSS denial, the jamming of radio frequency (RF) datalinks has become a feature of the electronic battlespace in Ukraine. Jammers are now deployed at scale, including fixed positions, portable infantry systems, vehicle-based platforms and airborne assets. The contest between measures to protect RF links and efforts to disrupt them has evolved into a continuous cycle of adaptation and counter-adaptation. Innovation occurs at high speed, with technical updates and tactical responses often emerging within days. While software upgrades can temporarily extend the life of existing UAV systems, hardware constraints impose hard limits. Once these are reached, platforms are withdrawn from service and replaced with new ones. This cycle drives the short operational lifespan of small UAVs such as FPVs.

The operational impact of jamming has put Russian EW systems among the top Ukrainian targeting priorities. It has also resulted in the need for complex deconfliction. Both Ukrainian and Russian UAVs often use overlapping frequencies, which increases the risk of fratricide through EW. Ukraine is developing software-based tools to manage this process, but challenges persist, particularly due to inconsistent coordination among separate units.[70]

## Uninhabited building

Both the enormous quantities of UAVs used, as well as the rapid cycles of innovation and obsolescence, pose challenges to the broader development and production industry for these systems. Ukraine and Russia have taken differing approaches.

In Ukraine, research and development (R&D) and production are organised in a predominantly horizontal fashion, involving a wide range of state entities, private companies, start-ups, non-profits and volunteer groups. The system quickly

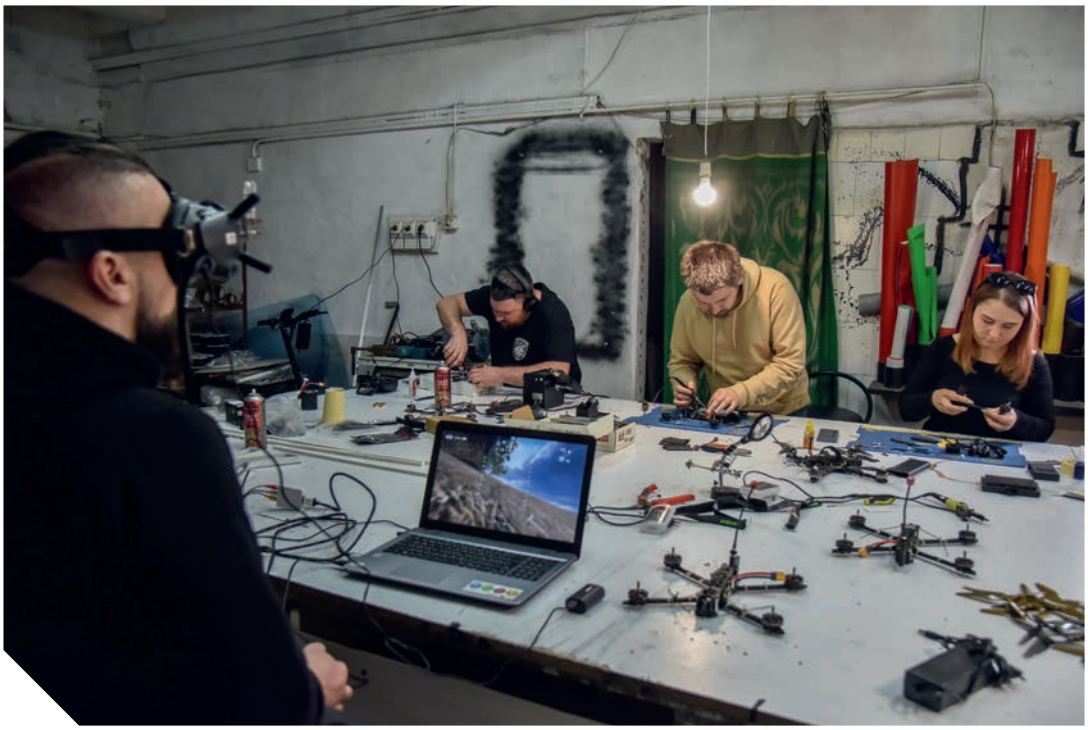
evolved in response to Russia's full-scale invasion, with only around 10% of companies currently active in UAV production having operated in this or related sectors before 2022. Ukraine's decentralised approach to UAV development and manufacturing has strengths and disadvantages. The Ukrainian UAV industrial pathway has demonstrated a high degree of adaptability and innovation, but its fragmented nature has resulted in reduced standardisation and greater variation in the quality of the systems produced compared to Russia.[71]

Russia's UAV industry, by contrast, appears more vertically integrated and state-controlled. This allows Russia to scale up production more quickly and achieve greater levels of standardisation. This approach, however, is viewed by Ukrainians as constraining innovation. This disadvantage, however, is offset at least in part because innovations introduced by one side often can be copied by the other. Russia's greater financial strength also allows it to make larger investments into experimentation, for example, fibre-optic cable-guided FPV development.[72]

The war has also revealed distinct R&D industries emerging for small FPV and multicopter UAVs, as well as larger OWA UAVs. In Ukraine, the first two are often produced by start-up companies and volunteer initiatives; many of the more complex and larger OWA UAVs have been designed and manufactured by larger companies. These include enterprises dating back to Soviet times, like Antonov, which specialised in transport aircraft. Whereas FPVs can become obsolescent relatively quickly, large OWA UAVs are more like traditional platforms, whose design can be upgraded rather than replaced.[73]

Current levels of UAV mass production observed in the conflict would likely be unsustainable without the supply of affordable, off-the-shelf components, including microelectronics, motors and batteries. Both Ukraine and Russia face challenges in this area. Russia has been affected by Western sanctions aimed at restricting access to critical components. Ukraine, meanwhile, has faced limitations from China on the direct export of certain items. Both countries have sought to overcome such constraints through efforts to produce key subcomponents domestically and using intermediaries to acquire foreign parts.[74]

In Ukraine, the provision of a highly diverse range of foreign UAVs has added a further layer of complexity. While some systems have been effective in combat, others have proven to be of low quality or poorly suited to the operational environment. To address these issues, Ukraine established a formal testing and certification programme for both domestic and foreign UAVs, required for entry into military service. At the same time, the intensity of the Ukrainian theatre



Volunteers assembling FPV drones in Lviv, Ukraine, 29 February 2024

Photo by Pavlo Palamarchuk/SOPA Images/LightRocket via Getty Images

has provided Western manufacturers with an opportunity to test their systems in combat and integrate Ukrainian feedback.

## Precedent-setting?

A combination of factors has driven the rapid and widespread adoption of small UAVs along the front line. These include the availability of affordable UAV platforms and components on the global market, the relatively high state capacity for procurement, production and deployment demonstrated by both Russia and Ukraine, and the positional stasis that has characterised much of the front line, prompting both sides to seek new tactical advantages.

The unprecedented scale of UAV use in Ukraine, including their ubiquitous use for ISR and strikes, has had a marked tactical impact. Broader implications, however, remain subject to debate, particularly concerning how far UAVs have fundamentally shaped the character of the conflict and what lessons other armed forces and organisations, including NATO, should draw from the Russian and Ukrainian experience.

Some observers have argued that the widespread availability of affordable UAV-based ISR and strike assets has played a central role in turning the conflict into a static war of attrition.[75] The availability of ISR is such that it has resulted in what some analysts have described as a 'transparent battlefield'. In such an environment, the concealed or protected build-up of forces needed to achieve breakthroughs in heavily defended front lines has become extremely difficult to achieve.[76]

A further argument is that the widespread distribution of UAV-based reconnaissance and strike capabilities has rendered traditional mechanised warfare, long considered the primary method for exploiting breakthroughs in static defensive lines, increasingly challenging.[77] The mix of ISR and attack UAVs now deployed can be used to detect and engage armoured vehicles, with the former available in far greater numbers than the armoured platforms themselves. Russia's response has been to abandon concentrations of armour for assaults in favour of more dispersed and survivable approaches, including small-unit infantry actions and motorcycle-mounted raids.[78] They have also fielded heavily protected vehicles known as 'turtle tanks', designed to withstand UAV attacks.[79] None of these adaptations has so far reintroduced a meaningful degree of massed tactical mobility on the battlefield.

The cumulative effect of UAV use in Ukraine has led some analysts to draw comparisons with the early phases of the First World War, before the large-scale introduction of tanks, when the growing firepower produced an operational imbalance that favoured defence and resulted in a static battlefield.[80] The impact of low-cost UAVs, it has been argued, has been so profound that it could eventually render obsolete entire classes of legacy systems.

This assessment typically refers to two dynamics. The first concerns platforms that have become increasingly vulnerable to UAV-based attacks, such as main battle tanks, which some argue are no longer survivable in an environment characterised by dispersed and persistent reconnaissance-strike capabilities.[81] The second relates to traditional strike systems, including artillery and crewed combat aircraft, that may struggle to remain relevant as UAVs offer comparable effects at significantly lower cost and with greater flexibility.[82] A frequently cited example is the extreme cost asymmetry observed during Ukraine's *Operation Spiderweb*, in which inexpensive uninhabited systems were used to attack expensive combat aircraft.

Others have cautioned against drawing erroneous conclusions from an incomplete picture of the war in Ukraine, given the partial and selective nature of available data. While videos of inexpensive FPV drones destroying high-value systems often go viral, they can offer a distorted picture of a particular system's effectiveness. FPV operators regularly emphasise the limitations of these systems, including low hit rates, modest destructive power, sensitivity to weather conditions, slow engagement timelines and vulnerability to EW. Operators have also noted that, in many cases, precise artillery fire, if available, would be faster, cheaper and more effective than employing FPVs.[83]

Similar uncertainties surround the use of OWA UAVs. The narrative of exceedingly cheap systems, sometimes made from materials like plywood, overcoming advanced air defences to strike critical facilities in Russia's depth can appear compelling. At the same time, there is very little public, comprehensive and verified data on the actual cost–benefit balance of these attacks or how they compare to more advanced systems. Officials involved in OWA operations, much

UK Prime Minister Keir Starmer inspecting a Ukrainian UAV in Kyiv, 16 January 2025

Photo by Carl Court via Getty Images

like FPV operators, often stress the limitations of these weapons. These include small payloads, the inability to strike hardened targets, the need for complex mission planning and relatively low numbers reaching their targets. While FPV operators tend to contrast their systems with precise artillery fire, OWA operators more often compare their missions to cruise-missile strikes, noting that in many cases the use of advanced cruise missiles or a high–low mix of cruise missiles and cheap OWA platforms would likely prove more effective.[84]

Another caveat is that the war in Ukraine reflects a specific operational context shaped by the conditions of the theatre. In Ukraine, the rapid increase in small-UAV use only occurred after front lines had already been fortified, suggesting that UAVs may have reinforced an existing operational reality rather than creating one. Ukraine's August 2024 incursion into Russia's Kursk *oblast*, although ultimately unsuccessful in holding territory, demonstrated that with careful planning, surprise and momentum remain feasible, even in a battlespace saturated by UAVs.[85] Russia's subsequent reconquest of the area further underlined this point.

Some have also argued that the static nature of much of the front line reflects, at least in part, the strategic cultures of the forces involved. Despite extensive reform efforts, the Russian military reflects a Soviet legacy that favours rigidity and relatively static modes of operation. Ukraine, however, has made progress in adopting a more agile military culture that incorporates elements of mission command, but it too remains influenced by aspects of the same inheritance. This stands in contrast to NATO's strategic culture, which has traditionally placed a strong emphasis on mobility and would therefore require a fundamentally different approach to the employment of UAVs.[86]

Furthermore, this war involves two actors with industrial, financial, technological and operational limitations. These constraints have shaped how UAVs are employed and may have precluded alternative forms of UAV use from emerging or being tested in practice.

A case in point is the interplay between UAVs and crewed combat aircraft, or, more often, the lack thereof. Facing effective GBAD, neither Russia nor Ukraine has currently achieved air superiority. Consequently, both have relied on using UAVs to conduct strikes that might otherwise be carried out by crewed combat aircraft. In this sense, UAVs have sometimes served as a substitute for traditional airpower.

This distinction is illustrated by comparing Israel's use of small UAVs against Iranian air defences in the opening phase of the Twelve-Day War in 2025 and Ukraine's *Operation Spiderweb* against Russian strategic bombers, conducted only weeks earlier. Although both operations featured similar technologies, their underlying logic was almost entirely reversed. Ukraine utilised such systems to compensate for the limited combat radius of its crewed combat aircraft, thereby addressing its inability to use these to strike targets deep within Russia. Israel, by contrast, used

similar systems to suppress enemy air defences to enable conventional air operations.

Limitations in the current Russia–Ukraine conflict also extend to the types and configurations of UAVs in use. Capabilities such as MALE UAVs equipped for persistent airborne early warning, long-range stand-off ISR using ground-moving target indicators, or maritime patrol might be of great value to both sides, but remain unavailable to either. The same also applies to capabilities that are still in development, such as collaborative combat aircraft or remote carriers operating in human–machine-teaming configurations. These systems are a focus of Western UAV development and, in large part, are intended to enhance survivability in contested environments, such as the one observed in Ukraine.[87] Yet being neither operational nor available to either side, their wider operational impact remains untested.

Finally, the war in Ukraine represents a specific moment not only in the evolution of UAV technology but also in the evolution of counter-UAV technologies, as well as associated operational concepts. Even assuming the current balance indeed favours the defender on the ground, thereby contributing to the emergence of static wars of attrition, this state might not persist. Governments, as well as industries, are investing in improved and novel counter-UAV capabilities, including directed-energy weapons, automated gun turrets and interceptor UAVs. Advances in these areas could restore greater freedom of movement for ground forces and better manage the threat to manoeuvre-based offensive operations.

## Conclusion

The scale of the use of UAVs in the Russia–Ukraine war is unprecedented. This alone would mark the conflict's significance regarding uninhabited systems. Further notable, however, was the military adaptation exhibited by the combatants in the use of UAVs. FPV UAVs have been predominant along a mainly static front line in a war of attrition, while OWA UAVs have also gained far greater prominence. Conversely, the use of the current generation of MALE UAV designs has been constrained by their vulnerability when operated within the engagement zone of GBAD systems. Changes in operation, defensive aids and increased sensor ranges will allow the threat to be managed to some extent. Still, in a highly contested air environment, survivability will remain an issue if operated within range of air defence.

The prevalence of UAVs above and around the battlefield has led to increased attention on EW. The capacity to utilise the electromagnetic spectrum in a peer-on-peer fight will need to be continually defended, as will the ability to operate in a degraded or denied environment.

One constant in the war has been the demand for ISR, and UAVs will continue to offer a key capability in addressing such needs.

## Endnotes

1 David Axe, '4.5 Million Drones Is a Lot of Drones. It's Ukraine's New Production Target for 2025', *Forbes*, 12 March 2025, https://www.forbes.com/sites/davidaxe/2025/03/12/45-million-drones-is-a-lot-of-drones-its-ukraines-new-production-target-for-2025/; and interview with Ukrainian official, 2025.

2 Marc Santora and Tyler Hicks, 'Russia Intensifies Assaults on an Exhausted Ukraine', *New York Times*, 20 November 2024, https://www.nytimes.com/2024/11/20/world/europe/russia-ukraine-war-attacks-trump.html.

3 'A View from Above', OSCE Special Monitoring Mission to Ukraine, 25 February 2021, https://www.osce.org/special-monitoring-mission-to-ukraine/479732; and Cono Giardullo, Walter Dorn and Danielle Stodilka, 'Technological Innovation in the OSCE: The Special Monitoring Mission in Ukraine', in Ursel Schlichting (ed.), *OSCE Yearbook 2019* (Baden-Baden: IFSH, 2020), pp. 119–37.

4 Sergey Sukhankin, 'Blind, Confuse and Demoralize: Russian Electronic Warfare Operations in Donbas', The Jamestown Foundation, 27 August 2021, https://jamestown.org/program/blind-confuse-and-demoralize-russian-electronic-warfare-operations-in-donbas/.

5 Phil Stewart, 'Exclusive: U.S.-supplied Drones Disappoint Ukraine at the Front Lines', Reuters, 21 December 2016, https://www.reuters.com/article/world/exclusive-us-supplied-drones-disappoint-ukraine-at-the-front-lines-idUSKBN14A26C/.

6 Ragip Soylu, 'Ukraine Received 50 Turkish Bayraktar TB2 Drones Since Russian Invasion', Middle East Eye, 28 June 2022, https://www.middleeasteye.net/news/russia-ukraine-war-tb2-bayraktar-drones-fifty-received.

7 Stijn Mitzer et al., 'A Monument of Victory: The Bayraktar TB2 Kill List', Oryx, 23 February 2022, https://www.oryxspioenkop.com/2021/12/a-monument-of-victory-bayraktar-tb2.html.
8 Thomas Newdick, 'Ukraine Claims TB2 Drones Sunk Russian Patrol Boats Off Snake Island (Updated)', *TWZ*, 2 May 2022, https://www.twz.com/ukraine-claims-tb2-drones-sunk-russian-patrol-boats-off-snake-island.
9 Interview with Western official, 2024.
10 Alexander Mladenov, 'Russia's Intense Air and Missile Defence Operation in Ukraine War', *Key.Aero*, 27 July 2023, https://www.key.aero/article/russias-intense-air-and-missile-defenceoperation-ukraine-war.
11 Interview with Ukrainian official, 2024.
12 Bryant Harris, 'Senators Urge Pentagon to Send Advanced Gray Eagle Drones to Ukraine', *Defense News*, 22 November 2022, https://www.defensenews.com/congress/2022/11/22/senators-urge-pentagon-to-send-advanced-gray-eagle-drones-to-ukraine/.
13 Gordon Lubold and Nancy A. Youssef, 'U.S. Refuses Advanced Drones for Ukraine to Avoid Escalation with Russia', *Wall Street Journal*, 9 November 2022, https://www.wsj.com/articles/u-s-wont-give-ukraine-advanced-drones-to-avoid-escalation-with-russia-11668042100?msockid=3515fb1416546288odboeed4174163fe.
14 Dylan Malyasov, 'Ukrainian Soldiers Seize Iranian-made Mohajer-6 Drone', *Defence Blog*, 4 October 2022, https://defenceblog.com/ukrainian-soldiers-seize-iranian-made-mohajer-6-drone/.
15 Yaakov Katz, 'IAI Embarks on Drone-manufacturing Venture with Russia', *Jerusalem Post*, 23 December 2010, https://www.jpost.com/defense/iai-embarks-on-drone-manufacturing-venture-with-russia; and ODIN, 'Forposts Russian Reconnaissance Unmanned Aerial Vehicle (UAV)', https://odin.tradoc.army.mil/WEG/List/ORIGIN_russia--rus--f8577e&DOM_unmanned-aerial-vehicles--uavs--bc8e46.
16 'Exclusive Access to the Russian Forpost Drone Shot Down in Ukraine', Bellingcat, 13 June 2015, https://www.bellingcat.com/news/uk-and-europe/2015/06/13/the-russian-forpost-drone-shot-down-in-ukraine/.
17 Lucas Winter, 'Russia Highlighting Use of "Cube" and "Lancet" Loitering Munitions in Syria', OE Watch, 2 February 2022, https://oe.tradoc.army.mil/product/russia-highlighting-use-of-cube-and-lancet-loitering-munitions-in-syria/; and Thomas Newdick, 'Russia Provides a Glimpse of Its Orion Drone Executing Combat Trials in Syria', *TWZ*, 22 February 2021, https://www.twz.com/39381/russia-provides-a-glimpse-of-its-orion-drone-executing-combat-trials-in-syria.
18 Interview with Ukrainian official, 2024.
19 'Ukrainian Paratroopers Shot Down Russian Orion UAV in the Kursk Region', *Defense Express*, 21 October 2024, https://en.defence-ua.com/events/ukrainian_paratroopers_shot_down_russian_orion_uav_in_the_kursk_region-12257.html.
20 'The Use of the Pacer UAV in the Special Operation', Next War, 12 September 2024, https://nextwar.clan.su/news/primenenie_bpla_inokhodec_v_specoperacii/2024-09-12-43314; and interview with Ukrainian official, 2024.
21 Patrick Tucker, 'Ukraine's Drone Warriors', Atlantic Council, 10 March 2015, https://www.atlanticcouncil.org/blogs/natosource/ukraine-s-drone-warriors/.
22 David Hambling, 'Russia Wants a Pretext for War and These Drones Could Supply It', *Forbes*, 18 February 2022, https://www.forbes.com/sites/davidhambling/2022/02/18/russia-wants-a-pretext-for-war-and-these-drones-could-supply-it/.
23 John Wendle, 'The Fighting Drones of Ukraine', *Air & Space Magazine*, February 2018, https://www.smithsonianmag.com/air-space-magazine/ukraines-drones-180967708/.
24 Ronald Watkins, 'Ukraine Unveils the Sokil-300, Its First Domestic Combat Drone', Defense Post, 12 November 2020, https://thedefensepost.com/2020/11/12/ukraine-unveils-sokil-300-drone/; and 'Antonov Unveils Long-endurance Unmanned Aircraft System Concept', UAS Weekly, 10 October 2018, https://uasweekly.com/2018/10/10/antonov-unveils-long-endurance-unmanned-aircraft-system-concept/.
25 Stewart, 'Exclusive: U.S.-supplied Drones Disappoint Ukraine at the Front Lines'.
26 Illia Ponomarenko, 'Turkish Bayraktar Strike Drones Pass Tests in Ukraine (VIDEO)', *Kyiv Post*, 20 March 2019, https://archive.kyivpost.com/ukraine-politics/turkish-bayraktar-strike-drones-pass-tests-in-ukraine-video.html; and 'Ukraine to Buy 5 More Turkish Bayraktar TB2 Drones in 2021', *Daily Sabah*, 27 November 2020, https://www.dailysabah.com/business/defense/ukraine-to-buy-5-more-turkish-bayraktar-tb2-drones-in-2021.
27 'Ukrainian Navy Has Received First Unit of Turkish-produced Bayraktar TB2 UCAV System', *Defence Express*, 18 July 2021, https://en.defence-ua.com/news/ukrainian_navy_has_received_first_unit_of_turkish_produced_bayraktar_tb2_ucav_system-1942.html.
28 'Ukraine Uses Turkish Drone Against Russia-backed Separatists for First Time', Radio Free Europe/Radio Liberty, 27 October 2021, https://www.rferl.org/a/ukraine-turkish-drone-separatists/31532268.html.
29 Kateryna Bondar, 'Does Ukraine Already Have Functional CJADC2 Technology?', Center for Strategic

and International Studies, 11 December 2024, https://www.csis.org/analysis/does-ukraine-already-have-functional-cjadc2-technology.

30 Lara Jakes, 'For Western Weapons, the Ukraine War Is a Beta Test', *New York Times*, 15 November 2022, https://www.nytimes.com/2022/11/15/world/europe/ukraine-weapons.html.

31 'Ukraine's Drone Production Go Through the Roof: Plan to Make One Million in 2024 Exceeded', *Defense Express*, 24 October 2024, https://en.defence-ua.com/industries/ukraines_drone_production_go_through_the_roof_plan_to_make_one_million_in_2024_exceeded-12296.html; and 'How Many Drones Did Ukraine Produce in 2024', Censor.NET, 23 February 2025, https://censor.net/en/news/3537464/how_many_drones_did_ukraine_produce_in_2024.

32 David Kirichenko, 'Fiber Optic Drones Could Play Decisive Role in Russia's Summer Offensive', Atlantic Council, 29 May 2025, https://www.atlanticcouncil.org/blogs/ukrainealert/fiber-optic-drones-could-play-decisive-role-in-russias-summer-offensive/.

33 Franz-Stefan Gady, 'The Air Battle that Could Decide the Russia–Ukraine War', *Foreign Policy* blog, 23 July 2025, https://foreignpolicy.com/2025/07/23/ukraine-war-drone-air-battle-russia-technology-tactics/.

34 Matthew Bint and Fabian Hinz, 'Russia Doubles Down on the Shahed', IISS Military Balance Blog, 14 April 2025, https://www.iiss.org/online-analysis/military-balance/2025/04/russia-doubles-down-on-the-shahed/.

35 Jennie Olmsted et al., 'Russian Offensive Campaign Assessment, July 20, 2025', Institute for the Study of War, 20 July 2025, https://www.understandingwar.org/backgrounder/russian-offensive-campaign-assessment-july-20-2025.

36 Interview with Ukrainian official, 2024.

37 UK Ministry of Defence (@DefenceHQ), 'Latest Defence Intelligence Update on the Situation in Ukraine, 23 December 2024', post to X, 23 December 2024, https://x.com/DefenceHQ/status/1871135225339597149.

38 Rob Lee (@RALee85), 'Videos from the Past Two Weeks of Russian Shahed Strikes in Sumy and Donetsk Oblast', post to X, 3 July 2025, https://x.com/RALee85/status/1940788898386280645.

39 'Russian Shahed Drones Now Equipped with Mesh Modems and Cameras, Wreckage Analysis Shows', *Defense Express*, 11 September 2025, https://en.defence-ua.com/weapon_and_tech/russian_shahed_droness_now_equipped_with_mesh_modems_and_cameras_wreckage_analysis_shows-15781.html.

40 David Hambling, 'Drone Attack on Moscow: Why It May Not Have Been the Ukrainian Government', *Forbes*, 30 May 2023, https://www.forbes.com/sites/davidhambling/2023/05/30/ukraine-has-a-growing-arsenal-of-drones-able-to-hit-moscow/.

41 H.I. Sutton, 'Guide to Ukraine's Long Range Attack Drones', *Covert Shores*, 6 July 2025, http://www.hisutton.com/Ukraine-OWA-UAVs.html.

42 Interview with Ukrainian official, 2024; and Laura Gozzi, 'Ukraine War: Deepest Ukraine Drone Attack into Russian Territory Injures 12', BBC News, 2 April 2024, https://www.bbc.com/news/world-europe-68712158.

43 Illia Kabachynskyi, 'Ukraine's Expanding Long-range Missile Arsenal: "Neptune", "Palianytsia", "Peklo", and "Ruta"', United24 Media, 3 July 2025, https://united24media.com/war-in-ukraine/ukraines-expanding-long-range-missile-arsenal-neptune-palianytsia-peklo-and-ruta-4392.

44 Shahryar Pasandideh, 'Video Offers a Glimpse of a Russian Turbojet-powered Version of the Shahed-136/Geran/Garpiya Strike Drone, Which May or May Not Be Related to the Geran-3', SPAS Consulting, 29 July 2025, https://www.spasconsulting.com/p/video-offers-a-glimpse-of-a-russian-01d.

45 Interview with Ukrainian official, 2024.

46 Max Hunder, 'Cheap Russian Drone a Menace to Ukrainian Troops and Equipment', Reuters, 28 June 2023, https://www.reuters.com/world/europe/cheap-russian-drone-menace-ukrainian-troops-equipment-2023-06-28/.

47 David Hambling, 'Russia Steps Up Deployment of Lancet Kamikaze Drones, but How Effective Are They?', *Forbes*, 25 June 2024, https://www.forbes.com/sites/davidhambling/2024/06/25/russia-steps-up-deployment-of-lancet-kamikaze-drones-but-how-effective-are-they/.

48 Alisa Yurchenko, 'Investigation: Who Helped Russians Increase Production of Domestic Attack Drones Despite Sanctions', Kyiv Independent, 21 November 2024, https://kyivindependent.com/investigation-who-helped-russians-increase-production-of-domestic-attack-drones-despite-sanctions/.

49 Hunder, 'Cheap Russian Drone a Menace to Ukrainian Troops and Equipment'; and David Hambling, 'The U.S. Army Won't Buy Any More Switchblade 300 Kamikaze Drones', 19FortyFive, 23 July 2023, https://www.19fortyfive.com/2023/07/the-u-s-army-wont-buy-anymore-switchblade-300-kamikaze-drones/.

50 Interview with Ukrainian UAV operator, 2024.

51 Ukraine Defence Intelligence (HUR), 'War & Sanctions: What Makes Russian FPV Drone Molniya and Orlans' Analog Phoenix Fly', 10 December 2024,

https://gur.gov.ua/en/content/war-sanctions-zavdiaky-chomu-litaiut-rosiiski-fpv-kryla-molnyia-ta-analoh-orlanu-fenyks.

52 David Ignatius, 'How Ukraine's Tech Army Is Taking the Fight to Russia', *Washington Post*, 5 April 2024, https://www.washingtonpost.com/opinions/2024/04/05/ukraine-russia-tech-drone-warfighting.

53 Interviews with Ukrainian officials and industry representatives, 2024.

54 Ukraine Ministry of Defence,'Enemy Equipment Detected in 2 Seconds: The Ministry of Defence Showcased DELTA and Avengers Systems at the London Defence Conference', 13 May 2025, https://mod.gov.ua/en/news/enemy-equipment-detected-in-2-seconds-the-ministry-of-defence-showcased-delta-and-avengers-systems-at-the-london-defence-conference.

55 Interviews with Ukrainian officials and industry representatives, 2024.

56 'Barrage Munition with Artificial Intelligence V2U', War & Sanctions, https://war-sanctions.gur.gov.ua/en/page-uav-v2u.

57 Ukraine Defence Intelligence (HUR),'War & Sanctions Reveals Components of Upgraded Iranian Shahed-136 Drone with Camera and AI', 27 June 2025, https://gur.gov.ua/en/content/warsanctions-rozkryvaie-nachynku-modernizovanoho-shahed136-vyrobnytstva-iranu-z-kameroiu-ta-shtuchnym-intelektom.

58 David Hambling, 'Ukraine Drone Carriers Launch First Long-range Autonomous Strikes', *Forbes*, 26 May 2025, https://www.forbes.com/sites/davidhambling/2025/05/26/ukraine-drone-carriers-launch-first-long-range-autonomous-strikes/.

59 Interviews with Ukrainian officials and industry representatives, 2024.

60 'Ukraine's Defense Intelligence: "Mini Shahed" Can Hit Moving Targets, but That's Not the Main Danger', *Defense Express*, 24 July 2025, https://en.defence-ua.com/weapon_and_tech/ukraines_defense_intelligence_examines_mini_shahed_capable_of_targeting_moving_objects_but_its_real_threat_lies_elsewhere-15237.html; and 'From Plywood to the Battlefield: Russia's Cheap Gerbera Drones Challenge Ukraine's Air Defenses', *Kyiv Post*, 19 November 2024, https://www.kyivpost.com/post/42444.

61 Serhii Flash, post to Telegram, 24 May 2025, https://t.me/serhii_flash/5631.

62 Stefan Soesanto, 'The Ukrainian Way of Digital Warfighting: Volunteers, Applications, and Intelligence Sharing Platforms', Center for Security Studies (CSS), 29 July 2024, https://css.ethz.ch/en/center/CSS-news/2024/07/the-ukrainian-way-of-digital-warfighting-volunteers-applications-and-intelligence-sharing-platforms.html.

63 Bondar, 'Does Ukraine Already Have Functional CJADC2 Technology?'.

64 Interview with Ukrainian officials and industry representatives, 2024.

65 Max Zander, 'Ukraine's "Nemesis" Drone Could Be a War Game Changer', Deutsche Welle, 1 July 2025, https://www.dw.com/en/ukraine-russia-war-drones-drone-warfare-starlink-internet-v2/video-73100019.

66 'Russia Equipped Shahed-136 with Starlink: Now Real-time Data Can Be Accessed at Distances Up to 2000 km', *Defense Express*, 26 September 2024, https://en.defence-ua.com/news/russia_equipped_shahed_136_with_starlink_now_real_time_data_can_be_accessed_at_distances_up_to_2000_km-11981.html.

67 Mary Ilyushina, 'Ukraine's Drones Disrupt Russia with Airport Closures, Internet Blackouts', *Washington Post*, 24 May 2025, https://www.washingtonpost.com/world/2025/05/24/russia-ukraine-drone-disruptions/.

68 Interviews with Ukrainian officials and UAV operators, 2024.

69 Sasha Vakulina, 'Lost and Spoofed. How Ukraine Redirects Russian Drones to Belarus', *Euronews*, 4 December 2024, https://www.euronews.com/my-europe/2024/12/04/lost-and-spoofed-how-ukraine-redirects-russian-drones-to-belarus; and Kyrilo Kushnikov, 'New Chinese CRPA Antenna Found on Russian Shahed', Militarnyi, 22 March 2025, https://militarnyi.com/en/news/new-chinese-crpa-antenna-found-on-russian-shahed/.

70 Interviews with Ukrainian officials and UAV operators, 2024.

71 Interviews with Ukrainian officials and industry representatives, 2024.

72 *Ibid*.

73 *Ibid*.

74 *Ibid*.

75 Ian Lovett and Daniel Kiss, 'A Never-ending Supply of Drones Has Frozen the Front Lines in Ukraine', *Wall Street Journal*, 13 July 2025, https://www.wsj.com/world/europe/a-never-ending-supply-of-drones-has-frozen-the-front-lines-in-ukraine-ae29c581.

76 Franz-Stefan Gady, 'How an Army of Drones Changed the Battlefield in Ukraine', *Foreign Policy* blog, 6 December 2023, https://foreignpolicy.com/2023/12/06/ukraine-russia-war-drones-stalemate-frontline-counteroffensive-strategy/.

77 Lara Jakes, 'Do Tanks Have a Place in 21st-century Warfare?', *New York Times*, 20 April 2024, https://www.nytimes.com/2024/04/20/world/europe/tanks-ukraine-drones-abrams.html.

78 Angelica Evans et al., 'Russian Force Generation and Technological Adaptations Update May 7, 2025',

Institute for the Study of War, 7 May 2025, https://www.understandingwar.org/backgrounder/russian-force-generation-and-technological-adaptations-update-may-7-2025.

79 Mick Ryan, 'The Truth About Russia's Turtle Tanks', Lowy Institute, 21 June 2024, https://www.lowyinstitute.org/publications/truth-about-russia-s-turtle-tanks.

80 Stacie Pettyjohn, 'Evolution Not Revolution: Drone Warfare in Russia's 2022 Invasion of Ukraine', Center for a New American Security, 8 February 2024, https://www.cnas.org/publications/reports/evolution-not-revolution.

81 Michael Peck, 'The Century-long Reign of the Machine Gun Is Over, a Russian Strategist Argues', *Business Insider*, 16 March 2025, https://www.businessinsider.com/russia-fpv-drone-machine-gun-infantry-weapons-2025-3.

82 Ryan Pickrell, Mia Jankowicz and Jake Epstein, 'Elon Musk Says Human-piloted Fighter Jets Like the F-35 Are Obsolete. Drone Tech Can't Yet Fill the Gap', Business Insider, 26 November 2024, https://www.businessinsider.com/elon-musk-crewed-fighter-jet-f-35-obsolete-drone-technology2024-11.

83 Jakub Jajcay, 'I Fought in Ukraine and Here's Why FPV Drones Kind of Suck', *War on the Rocks*, 26 June 2025, https://warontherocks.com/2025/06/i-fought-in-ukraine-and-heres-why-fpv-drones-kind-of-suck/.

84 Interview with Ukrainian official, 2024.

85 Interview with Ukrainian official, 2025.

86 Interview with volunteer UAV operator, 2024.

87 Douglas Barrie et al., 'Collaborative Platforms and Contested MALE UAVs', IISS, 18 December 2024, https://www.iiss.org/research-paper/2024/12/collaborative-platforms-and-contested-male-uavs/.