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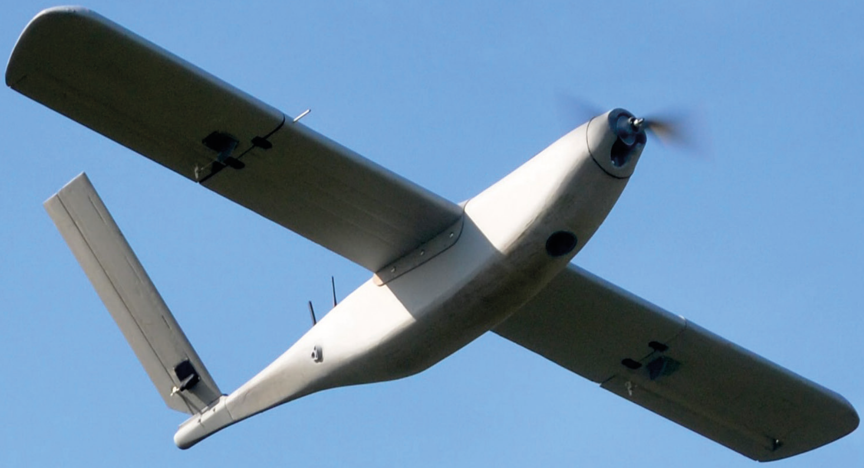
Mass Precision Strike
Designing UAV Complexes for Land Forces

Justin Bronk and Jack Watling



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Cover image: An experimental Ukrainian UAV surveils Russian positions in occupied Ukraine, 2022. Jack Watling

Royal United Services Institute
for Defence and Security Studies
Whitehall
London SW1A 2ET
United Kingdom
+44 (0)20 7747 2600
www.rusi.org
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Executive Summary

Russia's full-scale invasion of Ukraine has led to the extensive employment of UAVs to deliver precision effects at scale. Militaries observing the conflict are assessing how they can integrate these capabilities into their own forces and mitigate the threat from them. This paper is the first in a series. It examines how UAVs offer the most utility to land forces; subsequent papers will consider counter-UAV methodologies and their role across the joint force. There are six critical conclusions that can be drawn from the present paper.

First, UAVs' primary offer is their ability to deliver effect at either a cost or a scale that cannot be matched by other means. This means that UAV designs should be ruthlessly simplified and optimised for defined tasks. However, there are also limits to the extent to which costs can be driven down if a system is to be reliable and resilient. There are, in fact, very particular intersections between price and capability where UAVs are optimally effective.

Second, UAVs should be treated not as platforms but as systems. Any UAV becomes increasingly ineffective over time as the adversary refines its countermeasures. Ensuring that a UAV complex can continue to function effectively requires updates to software, behavioural logic, sensors and radios, every six to 12 weeks. The airframe is the constant but least important component. UAV procurement must reflect this, with suppliers contracted to provide subsystems, not integrated packages.

Third, the effectiveness of UAVs is largely determined by their layered employment, by crew skill, and by the capacity to plan flights. The latter requires access to electromagnetic surveys, meteorological data, intelligence on enemy air defences, and awareness of other UAV activity. The need to scale effect, and to have access to a support structure that must often draw on highly classified capabilities, means that while some UAVs may be widely distributed as tactical tools, most classes of UAV are better grouped into a specialist formation that is able to use different kinds of UAV in combination, and that has the in-house capacity to update and reconfigure its UAVs.

Fourth, a UAV battalion, equipped to deliver close and deep strike, deep ISR and enabling action, can support a large area of battlespace. While the capabilities they offer can pose challenges to the enemy, however, UAV effectiveness is ultimately dependent upon their interaction with artillery, electronic warfare, air defence and other force elements. UAVs may redistribute the balance of missions assigned to different systems, but they do not eliminate the requirement for traditional artillery.

The fifth critical conclusion is that regulation of UAVs is a major constraint upon their effective design, procurement and employment, and thus on their battlefield effectiveness. There are trade-offs between the speed of evolution necessary to keep these systems competitive and the safety requirements for airspace deconfliction. It is evident that the structures that exist in NATO countries today tend to increase cost and slow down development to such an extent as to prevent NATO states from employing UAVs effectively. The approach to regulation should be scrutinised, as it has an impact on the operational outputs of the force in this area.

Finally, a force that is aware of and equipped to counter the threat of massed UAVs can degrade their efficiency. There are many limitations to UAVs that can be worked around through adaptive tactics. These methods are difficult to scale. However, a force that is not aware of or equipped to counter UAVs risks ceding the enemy an insurmountable advantage in situational awareness, and suffering from a scale of precision effects that will prove crippling. Armies cannot, therefore, afford to be unprepared.

Introduction

This study addresses the question of what components are necessary for land forces to field a UAV complex that can deliver precision effects en masse to maximise the efficiency of exchange with an enemy. The study pursues this question by exploring three questions in sequence. The first chapter surveys the technological enablers of UAVs and the design trade-offs that ensue. The intent is to bound the resilience and scale of effect deliverable at a given price point. Having mapped where the utility and cost balance lies, the second chapter then explores the types of system a force must field in combination to maximise its effect. Having considered the number and type of UAV systems involved, the third chapter maps what is necessary as an enabling structure to deploy this scale of effect. The study also seeks to outline the limits of what can be achieved.

The paper draws on practical experimentation by the authors with most classes of military UAVs in NATO arsenals, and visits to sites and units engaged in the manufacture and testing of bespoke UAVs. The fieldwork included physical examination and technical inspection of Russian and Iranian UAVs, observation of UAV combat employment in Ukraine, and extensive interviews with manufacturers, operators, and troops responsible for countering UAVs. The authors also conducted a literature review of work on airframe design. Much of this research was undertaken in contexts where operational security or commercial sensitivity prevent direct attribution of data points in the present study. Therefore, the authors have attempted to find open-source material which replicates important data points or principles accurately where possible. This is the first study in a series: the second will outline a methodology for countering mass precision UAV strike complexes, while the third will consider how UAV and counter-UAV capabilities redistribute responsibilities and interactions across the joint force.

Since the 1980s, precision has been at the heart of the concept of a revolution in military affairs.[1] The efficiency of targeting using precision weapons was perceived by the Soviet Union to be as consequential for the conduct of war as the advent of nuclear weapons, while such capabilities sat at the centre of the US offset strategy during the Cold War.[2] The volume of precision strikes that a force can deliver has, however, been constrained by the cost and complexity of these

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[1] Mary C FitzGerald, 'Marshal Ogarkov and the New Revolution in Soviet Military Affairs', Center for Naval Analyses, CRM 87-2, January 1987, <https://apps.dtic.mil/sti/tr/pdf/ADA187009.pdf>, accessed 29 December 2023.

[2] Daniel Fiott, 'Europe and the Pentagon's Third Offset Strategy', *RUSI Journal* (Vol. 161, No. 1, 2016), pp. 26–31.

munitions,[3] making their allocation a key prioritisation decision in operation design.[4]

The advent of machine learning, miniaturised sensors and UAVs has driven widespread speculation about the ability to deliver precision strike at a previously unattainable scale.[5] UAVs carrying small payloads, delivering munitions precisely at the most vulnerable points, across the front, have dominated visions of future war in both science fiction and military theory.[6] Conceptually, the emphasis on precision strike has moved from limited numbers of prestige systems to cheap, attritable mass effects, especially in the land domain. These capabilities are not only presented as a novel strike system but are often touted as rendering a wide range of established military systems obsolete.

Most visions of mass precision strike do little to outline the limitations of cheap and attritable platforms. Nor do most of these studies outline how such a capability may drive an adversary to adapt its dispositions and capabilities. Furthermore, much of the emphasis in the literature is on the delivery mechanism – the UAV – while very little attention is given to supporting enablers or the formations required to field UAVs at scale. These enablers create vulnerabilities in a mass precision complex that have rarely been mapped, and consequently there has been little consideration of how a mass precision complex may need to be employed in order to assure its own survivability and effectiveness. Unpacking these considerations is vital as militaries begin to invest significantly in UAV technology. In the UK, for example, the Ministry of Defence has just committed £4.5 billion to UAV acquisition,[7] while Project Replicator in the US is set to receive several hundred million dollars' worth of funding.[8]

It is important to bound the scope of this study. One of the enduring sources of confusion about the impact of UAVs on the battlefield is the elasticity of the word

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3. Donald I Blackwelder, 'The Long Road to Desert Storm and Beyond: The Development of Precision-Guided Bombs', thesis, School of Advanced Airpower Studies, May 1992, <https://media.defense.gov/2017/Dec/28/2001861715/-1/-1/0/T_BLACKWELDER_ROAD_TO_DESERT.PDF>, accessed 29 December 2023.
4. US Air Force, Air University, Curtis E LeMay Center for Doctrine Development and Education, 'Basic Planning Considerations', in 'Air Force Doctrine Publication 3-03: Counterland Operations', 21 October 2020, <https://www.doctrine.af.mil/Portals/61/documents/AFDP_3-03/3-03-D25-PlanningConsid.pdf>, accessed 29 December 2023.
5. David Hambling, *Swarm Troopers: How Small Drones will Conquer the World* (London: Archangel, 2015).
6. For example, Mark Bowden, 'The Tiny and Nightmarishly Efficient Future of Drone Warfare', *The Atlantic*, 22 November 2022; T X Hammes, 'The Future of Warfare: Small, Many, Smart vs Few & Exquisite?', *War on the Rocks*, 16 July 2014; Peter Singer and August Cole, *Ghost Fleet: A Novel of the Next World War* (Boston, MA: Houghton Mifflin Harcourt, 30 June 2015).
7. MoD, 'New UK Strategy to Deliver Drones to Armed Forces', press release, 22 February 2024, <https://www.gov.uk/government/news/new-uk-strategy-to-deliver-drones-to-armed-forces>, accessed 26 February 2024.
8. Michael O'Connor, 'Replicator: A Bold New Path for DoD', Center for Security and Emerging Technology, 18 September 2023, <https://cset.georgetown.edu/article/replicator-a-bold-new-path-for-dod/>, accessed 26 February 2024.

'drone'. This term is used to cover everything from hand-sized UAVs designed for scouting buildings to long-endurance high-altitude aircraft such as the RQ-4 Global Hawk, which are comparable in size to a regional airliner and cost more than $100 million each.[9] There is a perennial tendency in the literature to describe a quadcopter costing around $2,500, and then to casually endow it with capabilities that would require processing power, battery, sensors, communications links and lift that are unlikely to be viable below a price point of around $80,000. This paper does not assume that a single airframe can achieve the range of effects required; this is why it is premised on the study of a mass precision strike complex. By 'complex', the paper means a grouping of UAV platforms that, as a system, offers a commander the ability to deliver mass precision effects. Complexes include the airframes and their payloads, and the launch crews, command links, planning tools, intelligence support and design teams required to field the capability. The precision strike complex is discussed as being formed of five UAV classes: situational awareness UAVs optimised for tactical reconnaissance; tactical strike UAVs; ISR UAVs able to penetrate into operational depth; operational strike UAVs; and platform-launched effects designed specifically to synchronise with and enable other weapons systems.

There are several systems that fall under the highly general term 'drone' that are excluded from this study. This study does not examine hand-held micro-UAVs, nor does it examine remotely piloted medium-altitude long-endurance UAVs such as the MQ-9 Reaper or the Bayraktar TB2, because these are optimised for operating in uncontested airspace.[10] The study considers expendable systems that might be launched by air forces, but does not consider full-scale loyal wingmen or uncrewed combat aerial vehicle-type platforms. Nor is this paper concerned with blue-water naval capabilities. The capabilities described are relevant to littoral naval operations, but naval engagements at sea are likely to employ UAVs in a range of bespoke roles that are beyond the scope of this study.

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[9] Hanan Zaffar, 'Japan Receives First of Three RQ-4B Global Hawks From US', *The Defense Post*, 18 March 2022, <https://www.thedefensepost.com/2022/03/18/japan-rq-4b-global-hawks/>, accessed 2 February 2024.

[10] Alia Shoaib, 'Bayraktar TB2 Drones were Hailed as Ukraine's Savior and the Future of Warfare. A Year Later, They've Practically Disappeared', *Business Insider*, 28 May 2023, <https://www.businessinsider.com/turkeys-bayraktar-tb2-drones-ineffective-ukraine-war-2023-5?r=US&IR=T>, accessed 2 February 2024.

I. UAV Design Trade-offs

A mass precision strike complex is not just a question of UAVs. Traditional barrel or rocket artillery will deliver precision effects, while electronic warfare (EW), geospatial and other ISR assets are fundamental to a robust reconnaissance strike complex. In theory, however, UAVs allow this complex to scale and mesh across echelons because of the ability to generate large numbers of ISR feeds and to economically deliver a high volume of precision effects, either by exploiting UAV-based ISR to make traditional artillery precise, or by delivering effects with UAVs. Given that it is the UAVs that sit at the nexus between precise and mass effect, understanding the design limitations and trade-offs inherent to UAVs is vital to grounding concepts of employment within the bounds of what is physically possible and worthwhile from a cost versus effect point of view. This chapter, therefore, details the design considerations that make up a UAV, from the airframe, propulsion and power requirements to the navigation and control mechanisms, sensors and payload.

Airframe

The airframe for any given UAV sets both the aerodynamic parameters and many of the performance and payload parameters. There are fundamental trade-off decisions that must be made during the formative design stages of any system. The starting point is to determine the range and payload weight and size required to perform a UAV's role in the mission set. These parameters will determine the options in terms of propulsion solutions, which in turn will impose fuel or battery capacity requirements on the airframe. Through a process called fuel match sizing – illustrated in Figure 1 – the required size of the airframe can be determined based on the fuel or battery capacity that must be carried to allow the available propulsion and aerodynamic configuration to carry the mission payload the distance and for the duration needed.[11]

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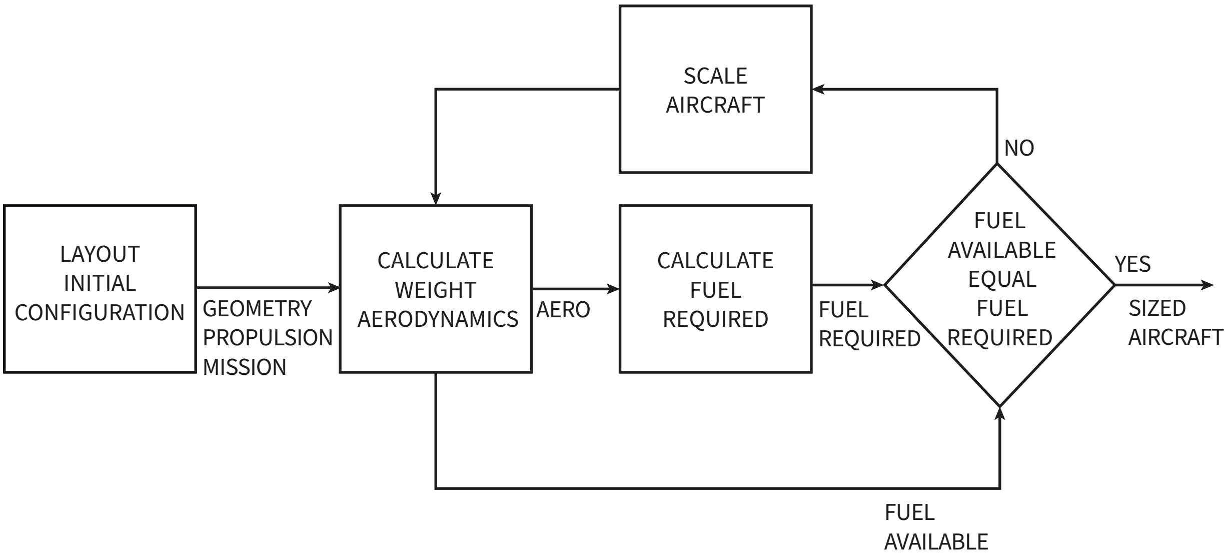
[11] J L Parker, 'Mission Requirements and Aircraft Sizing', in 'Special Course on Fundamentals of Fighter Aircraft Design', NATO Advisory Group for Aerospace Research and Development, AGARD Report No. 740, October 1987, p. 2-16, <https://apps.dtic.mil/sti/tr/pdf/ADA192214.pdf>, accessed 2 February 2024.

Figure 1: Fuel Match Sizing



Source: J L Parker, ‘Mission Requirements and Aircraft Sizing’, in ‘Special Course on Fundamentals of Fighter Aircraft Design’, NATO Advisory Group for Aerospace Research and Development, AGARD Report No. 740, October 1987, p. 2-16, <https://apps.dtic.mil/sti/tr/pdf/ADA192214.pdf>, accessed 2 February 2024.

As Figure 1 shows, the range and endurance required are crucial to determining the size, configuration and cost of the platform. The more range required, the greater the weight and size of the fuel or battery packs necessary to run the motors for a sufficient length of time, and therefore the greater the size and weight of the airframe. As the size and weight of the airframe increase, the power required for sustained flight at a given level of performance will also increase, meaning that the propulsion solution will consume more power per minute and thus the fuel/battery capacity needed will further increase, driving a commensurate increase in airframe size, and so on. Thus, relatively small increases in mission payload or range requirements can drive significant increases in overall airframe size, weight and cost.

Airframe configuration will also depend on the range and flight performance required. Broadly speaking, rotary engine configurations such as multi-copter UAVs are significantly less efficient in terms of fuel/battery power consumption over a given range and endurance compared to fixed-wing configurations.[12] However, they are capable of hovering in place, launching and recovering vertically in complex terrain, and making sharper turns than fixed-wing systems. Therefore, for many mission sets, the flexibility that a rotary configuration brings is worth the trade-off in endurance and payload for a given size and

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12. James Rennie, ‘Drone Types: Multi-Rotor vs Fixed Wing vs Single Rotor vs Hybrid VTOL’, AUAV, 8 November 2016, <https://www.auav.com.au/articles/drone-types/>, accessed 2 February 2024.

power. Fixed-wing configurations are more efficient in terms of how far and how long a given payload can be carried at a given price point and size. However, they also require a flat, open space to launch and recover (proportionate to the size of the platform), are unable to make sharp turns or stop and hover, and are more predictable in flight, making them easier for hostile forces to detect and engage.[13]

The airframe configuration of a traditional aircraft is a relatively fixed constraint once initially fuel-match sized and specified. The complexity of redoing aerodynamic, weight and balance, lift/drag and other calculations, and retooling factories to significantly different airframe specifications, has generally precluded major changes in size and layout once an aircraft is in production. However, recent developments in additive manufacturing and advanced machine-learning-enabled aerodynamics and flight control analysis have combined to make it easier to change airframe configurations rapidly, especially for smaller systems. In Ukraine, both sides make regular use of modular UAV components to iterate new and flexible copter-type configurations.[14] Firms also use additive manufacturing and computer-aided design suites to print UAV airframes for fixed-wing designs and tweak internal and even wing configurations as mission requirements evolve and operational usage data is collected. Therefore, airframe designs for massed strike complex assets are likely to be significantly more flexible and adaptable even once in production than traditional aircraft or even UAVs have been over the past century. This does come at the expense of reliability and safety, however.

There are limits to this adaptability, since changing the aerodynamics, size and payload needed for a system will unavoidably affect the power and lift required to keep the system airborne within its performance parameters. This will affect the fuel or battery power required, and so may drive further spiralling increases in required airframe power, size and ultimately cost. At a certain point, asking for just a little more range or a heavier or more power-hungry payload may drive the airframe configuration to a point where it is no longer economical to use in the quantities desired, or there may be a significant impact on platform reliability.

Other potentially significant airframe considerations include weather tolerances. Waterproofing for internal components to enable sustained operations in bad weather, as well as, potentially, heat dissipation or cooling features to enable payloads to function in very hot weather and de-icing features to enable winter operations, all add cost, weight and complexity. A good example of such a trade-off is where a UAV's intakes are located. Because UAVs often fly low, in a hot,

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13. Author interviews with Ukrainian air defence personnel with frontline counter-UAV experience, Ukraine, July 2023.
14. Author visits to Ukrainian UAV design and manufacturing facilities, Ukraine, October 2022 and July 2023.

dusty environment, a dorsally mounted intake improves reliability over a ventrally mounted intake. A dorsal intake tends, however, to have reduced reliability in rainy conditions.[15] Some companies have developed novel methods for thermal management to get around these issues, but such bespoke solutions push UAVs well outside the realm of commercial off-the-shelf components and so add significant cost. For all-weather capabilities, most airframes will need to be bespoke military designs.

Propulsion and Power

The choice of propulsion type is one of the fundamental factors that will set the boundaries of possibility for a UAV, weapon or aircraft. No matter what software or sensors an airframe is fitted with, the laws of physics will still determine the ranges, speeds and durations it can operate over, based on the amount of engine thrust available and the length of time for which this can be sustained. The three primary options for propulsion categories are propellers, jet turbines or rocket engines.

Propellers provide by far the greatest efficiency in terms of the amount of distance that can be covered for a given amount of fuel or battery power. They are also the simplest and cheapest solution, meaning that for assets that are intended to be fielded in very large numbers and be truly expendable, they are often the first choice. However, they are also the slowest in terms of cruise and dash speeds.

Propeller solutions can be powered by either electric motors or internal combustion engines, with electric power providing quieter operation, often cheaper and simpler installation, and potentially simpler logistics. However, a study in 2020 found that for UAVs, batteries store around 260 times less power for a given weight compared with gasoline.[16] Furthermore, this battery weight penalty for flight increases in a non-linear fashion with increases in the required range/endurance of a UAV mission. This is because, unlike fuel, which is burned over time and so decreases in weight as it is used up, spent battery packs still weigh the same as charged ones. This means that adding additional battery capacity to increase range gives less and less benefit as range increases, especially for systems that are not intended to be single-use one-way attack (OWA) assets. By contrast, combustion engines burning fuel generally involve a more complex airframe installation and make more noise but provide significantly greater

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[15] Experimentation conducted in the Atlantic comparing uncrewed aerial systems (UAS) types, June 2022.

[16] Ashleigh Townsend et al., 'A Comprehensive Review of Energy Sources for Unmanned Aerial Vehicles, Their Shortfalls and Opportunities for Improvements', *Heliyon* (Vol. 6, No. 11, November 2020), p. 3, <https://www.cell.com/heliyon/fulltext/S2405-8440(20)32128-9>, accessed 2 February 2024.

potential thrust and range.[17] As a result, for applications requiring light payloads over short ranges for limited periods, electrical power is generally the preferred solution, while the longer the required range and the heavier the payload, the more compelling combustion engines powered by fuels become.

Propeller-based propulsion solutions generally also produce a significant rotor sound signature that is easier than other forms of propulsion to detect, classify and track using passive acoustic sensors. This can be mitigated to some extent with specially designed propellers. Small and/or light rotor blades such as those found on most multi-copter UAVs also generally have significant limitations in cold weather environments due to icing problems, and at altitude.[18]

The second option for propulsion is jet turbines. The main attraction of a turbine solution is that it enables significantly higher airspeeds and potentially operational altitudes than propeller-based solutions. Therefore, where a system needs to cover distances quickly, a turbine propulsion solution is attractive. Depending on the design and size of the turbine, such a solution can also offer respectable fuel economy over long distances, but would still require more fuel than a propeller propulsion solution for a given range in most circumstances. Jet turbines cannot be used on purely electric platforms, and they are also significantly louder than propeller-based systems. Turbine engines are much more expensive than propeller engines, and their installation and the speeds at which they allow platforms to operate generally imply a more complex and sophisticated airframe configuration, increasing cost.

The final propulsion option is rocket motors. These can be powered by liquid or solid fuels, although for small systems, solid fuels are preferable because of their greater stability, which enables systems to be transported and stored in a ‘ready to use’ state. Solid-fuel rocket motors are also much simpler and cheaper than liquid-fuelled systems. Compared with both jet turbine and propeller propulsion options, rocket motors offer far greater static thrust and, therefore, much greater acceleration and top speed for a given size. However, they also burn fuel at a vastly greater rate and so only provide power for the initial few seconds of flight, leaving the platform to glide to its target from that point on using the kinetic and gravitational energy built up during launch. Rocket motor solutions offer much greater responsiveness but over a much shorter range than other propulsion options. Solid-fuel rocket motors are generally cheaper than a jet turbine propulsion solution.

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[17] *Ibid.*, pp. 5–8.

[18] For example, see Lauren Nagel, ‘A Study on Drone Propeller Icing at High RPM’, Tyto Robotics, 1 May 2023, <https://www.tytorobotics.com/blogs/articles/drone-propeller-icing-at-high-rpm>, accessed 2 February 2024.

Navigation

Precision is dependent upon accurate navigation and timing. If a UAV (or its operator) does not know where it is, then it cannot guide a munition, or itself, to an identified target unless the target is already in line of sight. The robustness of a UAV's navigation is fundamental to its utility.

The ubiquitous approach to navigation is to rely on global navigation satellite systems (GNSS), including GPS, Galileo, BeiDou and GLONASS. These systems all work through a similar logic. A constellation of satellites broadcast their location with a timestamp of the emission. A receiver can measure the difference between the time at which the signal was received and the timestamp of when it was sent to establish an accurate line of bearing.[19] By comparing four lines of bearing from different satellites, the receiver can triangulate its own relative position. The power of these navigational emissions is very low; they are, therefore, easy to receive, but also easy to jam through saturation of the frequencies used. Alternatively, adversaries can deliver false signals such that the receiver is spoofed into locating itself in an erroneous position.[20]

One partial solution to this is to receive on multiple GPS frequencies and even to have antennae scanning frequencies between GPS, BeiDou, Galileo and GLONASS, and compare the results.[21] If the results not only vary but also diverge or converge, then the receiver can either seek to confirm which signal to trust or else revert to another mode of navigation. This increases the complexity and cost of the receiving unit. Although it is possible for an enemy force to fully jam these navigational frequencies, it will rarely jam all of them because it will often be using some of them to determine the location of its own equipment. Nevertheless, if for a limited period the threat from UAVs renders it worthwhile to deny one's own navigation, then GNSS can be denied. To rely on this method of navigation is to make the capability hostage to the enemy's risk calculus.

The normal reversionary method is inertial navigation, enabling the UAV to plot its own location relative to a known starting position. To do this, the UAV must first know that it is being jammed and therefore assess when to revert, or else use inertial navigation with its launch point as its point of reference. The system must have a laser gyroscopic compass, a precise clock, a pitot tube measuring

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19. Federal Aviation Administration, 'Satellite Navigation – GPS – How it Works', <https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/gps/howitworks>, accessed 29 December 2023.
20. C4ADS, 'Above Us Only Stars: Exposing GPS Spoofing in Russia and Syria', 2019, <https://c4ads.org/wp-content/uploads/2022/05/AboveUsOnlyStars-Report.pdf>, accessed 29 December 2023.
21. Examination of multiple antenna arrays on Iranian- and Russian-manufactured OWA munitions, Ukraine, October 2022, July 2023 and February 2024.

airspeed, and a barometric or radar altimeter to establish altitude.[22] These requirements all add significant cost, meaning that it is difficult to produce UAVs which include such navigational capabilities and that can be sustainably expended en masse. Some of these systems – barometric altimeters, for example – are also more accurate when they are larger. In the case of barometric altimeters, a larger capacity of vacuum chamber improves sensitivity.

Inertial navigation systems are highly susceptible to becoming increasingly inaccurate over time, because they struggle to determine drift. It is therefore usually necessary for inertial navigation to intermittently recalibrate through external confirmation. This can be done with GNSS if it is available, with the potential for gaps in jamming, whether because of terrain or the enemy periodically lifting electronic protection. It can also be done through periodic triangulation using civilian infrastructure such as mobile phone masts.

Improving the reliability of location confirmation can, however, be achieved via other means. One such method is terrain recognition. If a platform has an electro-optical sensor and a pre-loaded map of the terrain over which it is flying, computer vision can be used to match the UAV's camera view against identifiable terrain features and physical markers such as rivers, roads and forests.[23] In some contexts, more novel navigation techniques can be employed. If a platform can roll and fly inverted, or if it has an additional electro-optical sensor facing upwards, then it can use triangulation from astronomical points of reference to confirm its position.[24]

Alternatively, if a platform has a laser range finder and flies at a low and level altitude, it can compare changes in contour of the ground over time to track its progress over its pre-loaded map.[25] Novel methods, however, are mission-specific and present significant vulnerabilities. Following terrain contours, for example, does not work if there is low cloud or if the ground is flat, featureless or snow-covered. Astral navigation is restricted to clear nights and requires medium-altitude flight. These techniques may, therefore, enable navigation for specific missions, but they are not generalisable. They also tend to be sufficiently accurate to get a munition over a target, but insufficient to strike it precisely.

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[22] UAV Navigation, 'Introduction to Altimeters', <https://www.uavnavigation.com/support/kb/general/inertial-navigation-system-and-estimation/introduction-altimeters>, accessed 29 December 203.

[23] Martial Hebert, 'Computer Vision for Autonomous Navigation', Carnegie Mellon University, 5 June 1988, <https://www.ri.cmu.edu/pub_files/pub3/hebert_martial_1988_3/hebert_martial_1988_3.pdf>, accessed 29 December 2023.

[24] David Hambling, 'The US Army's New Unhackable GPS Alternative: The Stars', *Popular Mechanics*, 25 April 2021, <https://www.popularmechanics.com/military/research/a36078957/celestial-navigation/>, accessed 29 December 2023.

[25] Jonghoon Seo et al., 'Fast Contour-Tracing Algorithm Based on a Pixel-Following Method for Image Sensors', *Sensors* (Vol. 16, No. 3, 2016), pp. 353–79.

Another very specific navigational tool, which can overcome limitations of terminal accuracy, is an emissions seeker that aligns a UAV to a particular target, such as specified radar emitters. Loitering munitions including Harpy and Harop can home in on enemy emitters and loiter when signals are lost.[26] In this way, they can have a suppressive effect. Such capabilities, however, are optimised for limited classes of target, and are susceptible to hard counters unless paired with other threat systems that impose conflicting imperatives on an adversary. Other systems, such as radar, can be used to align a munition in terminal dive in order to strike a specified area on an object. This kind of system works at short range, and while suitable for ensuring that a system working on inertial navigation can course correct to hit a specified target during its terminal dive, it requires an additional sensor to the inertial navigation system. Each additional sensor imposes an increase in cost, complexity, size and weight. Image recognition is another solution, but unless assisted by offboard data or human oversight, it is vulnerable to decoys, camouflage and other countermeasures.

The navigation methods discussed above are primarily for platforms that are designed to perform much of their navigation automatically, rather than under real-time human control. The latter requires an active command link between the UAV and the human operator during flight. For ISR platforms, such a link is necessary to offboard detections. For all UAVs, however, flying under control, with navigation conducted by a human operator, can obviate the need for the UAV to know its location. Where periodic human control in a contested electromagnetic spectrum is possible, this can also allow recalibration of inertial systems. The viability of this method is dependent upon power and the sophistication of the datalink being used to maintain control.

Datalinks

Radio frequency command links are generally only effective within line of sight, unless a relay is used. Power ultimately determines the strength of the command link and the ease with which it can be jammed. Jamming tends to affect the receiver through saturation. Thus, many UAVs can offboard data even when they are not able to receive it. For UAVs operating in tactical depth, their proximity to their controllers and the limitations on how far forward enemy jammers can be pushed makes it easier to maintain command links.[27] For UAVs pushing into enemy territory where the receiver is closer to enemy jammers than to friendly command transmitters, this becomes problematic.

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[26] IAI, ‘HARPY: Autonomous Weapon for All Weather’, <https://www.iai.co.il/p/harpy>, accessed 29 December 2023.

[27] Author observation of Ukrainian tactical UAV use and interviews with UAV operators and instructors, Ukraine, July 2023.

The robustness of these connections depends upon the complexity of the radio employed. If a UAV has a frequency-hopping radio, rapidly moving over a sufficient portion of the spectrum, then it is difficult to jam, though interference may corrupt or degrade data being transferred.[28] A dual-frequency receiver is often an effective way of giving some resilience without incurring the cost of a high-end frequency-hopping radio. Reliability can also be improved through directional beam riding, whereby only commands passed on a specific vector are accepted, thereby rendering jamming that is not aligned ineffective.[29]

Some specialist jamming equipment can track patterns in frequency hopping and craft bespoke interference patterns that degrade command links.[30] One way of obviating this is to have a group of UAVs passing data to one another, with each programmed to receive on different frequency regimes. If the contents of the data include a certification of authenticity, then each UAV that successfully receives authenticated data can confirm that it has received a correct command and then relay this to other UAVs in the same formation.[31] Another way in which UAVs can collaborate to overcome jamming, as well as extending the range of command, is to act as relays for one another, such that the command signal is emitted and received closer than the jammer is to the receiver, significantly increasing the power required by the jammer to suppress the signal. Although these kinds of techniques are viable, they depend upon sophisticated and therefore costly radios. They also rely on skilled operators to programme and set up the communications architecture.

Another form of command link that can be robust is a satellite link, since it is difficult for a jammer to achieve alignment against the antenna. Satellite links are also valuable for offboarding data over the horizon. The problem with satellite links is that they introduce significant latency into a system and are generally unsuitable for maintaining a platform under direct control.[32] Updating orders via satellite link is viable, but continuous correction of flight surfaces is more problematic. Robust satellite links depend upon highly effective gyro-stabilisation of the antenna, and are therefore only viable on larger airframes.

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28. Author manipulation of Russian radio sets, Ukraine, June 2022.
29. Author interviews with EW operators, September 2021.
30. Technical inspection of Russian Shipovnik-Aero counter-UAV jamming system, captured in Ukraine, October 2022.
31. Defense Advanced Research Projects Agency, ‘Collaborative Operations in Denied Environment (CODE) (Archived)’, <https://www.darpa.mil/program/collaborative-operations-in-denied-environment>, accessed 29 December 2023.
32. Sharon Weinberger, *The Imagineers of War: The Untold Story of DARPA, the Pentagon Agency that Changed the World* (New York, NY: Alfred Knopf, 2017), pp. 257–75.

Sensors

The sensors required for a UAV are dependent on both the effect needed when the component reaches its operational area and the navigation solution(s) being relied on to get it to that operational area. In an ideal world, the same sensor or group of sensors can be used for both, since minimising sensors required is crucial for conserving space, weight, power and computing (SWAP-C) capacity, and overall unit cost. This is not always possible, however.

Sensors can broadly be divided by the parts of the spectrum in which they operate. The simplest and most ubiquitous sensors are electro-optical (EO) cameras. Drawing on technological innovation and cost reduction driven by the commercial mobile phone sector, even small UAVs can be cheaply equipped with high-resolution EO cameras purchased in bulk from the civilian market. Advanced optical systems with high levels of magnification rely on more complex lens and stabilisation/vibration dampening technologies to be effective.[33] Therefore, the greater the stand-off range and altitudes that an optical sensor needs to be effective over, the more expensive, large and costly it will be. Another major driver of cost, size and complexity is the need for flexible, trainable mountings, as opposed to fixed camera mounts in an airframe.

Related to EO sensors are infra-red (IR) cameras, which use thermal imaging and can function in low light conditions. IR sensors can either be standalone or integrated into multispectral cameras that combine EO and IR capabilities. Both are more costly than basic EO cameras. However, if a UAV is to operate at night, the cameras must either be IR-capable, or the system must be modular and able to accept either an EO or an IR sensor fit – either way, complexity and cost increase. Image-intensifying capabilities, which take an EO sensor and maximise its performance in low light, can extend a UAV's utility into the night, but will struggle when there is minimal ambient light.[34] Both EO and IR cameras offer notable advantages for smaller UAVs. They require limited power to operate and are passive. They do not rely on emitting electromagnetic energy to function and so do not risk giving away the presence of the platform to hostile passive sensors when used. They are also difficult to jam, although they are vulnerable to camouflage measures and potentially to defensive laser-based systems that can use retro-reflection to detect cameras,[35] or dazzle or damage the optical

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[33] Chris Johnston, 'Meeting the Design Challenges for Imaging Payloads on Small UAVs', *Laser Focus World*, 1 April 2013, <https://www.laserfocusworld.com/detectors-imaging/article/16556976/defense-security-meeting-the-design-challenges-for-imaging-payloads-on-small-uavs>, accessed 2 February 2024.

[34] For information on the development of night vision cameras over time, see Harry P Montoro, 'Image Intensification: The Technology of Night Vision', *Photonics Spectra*, March 2009, <https://www.photonics.com/Articles/Image_Intensification_The_Technology_of_Night/a25144>, accessed 2 February 2024.

[35] Omron, 'Technical Explanation for Photoelectric Sensors', CSM Photoelectric_TG_E_8_3, <https://www.ia.omron.com/data_pdf/guide/43/photoelectric_tg_e_8_3.pdf>, accessed 29 December 2023.

sensors.[36] EO and IR cameras also do not work through clouds, fog, snow or heavy rain. Therefore, UAVs cannot exclusively rely on cameras if the complex that they are part of needs an all-weather capability.

Another category of sensor is radio detection and ranging (radar). Radar can be subdivided into passive and active systems, and by the frequency band that each system is designed to operate in. In general, the higher the frequency and shorter the wavelength a radar operates at, the higher resolution it can offer, but the shorter its effective range for any given power level.[37] Longer-wavelength systems also require larger apertures to function effectively, and so most radar sensors small enough to be mounted on a UAV will be higher-frequency, shorter-range systems. Passive radar systems only have the ability to 'listen' for reflected radar energy from external emitters, while active radar systems broadcast and then 'listen for' the returns from their own energy. The latter is more flexible and reliable, but allows for tracking of the UAV.

For UAVs, radars are often used for synthetic aperture radar mapping, where active radar signals are emitted and the returns from all ground objects and terrain are used to build up a radar 'image' of an area.[38] Radars can also be used for detection of other airborne objects, and for terrain mapping for navigation in any weather. Some advanced weapons and OWA UAV designs also use millimetric radar seekers to scan for and provide pinpoint terminal guidance against vehicles and other reflective targets.[39] This allows weapons to perform automatic target search and guidance, but at a significant cost and complexity premium. In general, the biggest benefit of radar-based sensors is that they work equally well in bad weather or at night, while the disadvantages include greatly increased power and cooling requirements, as well as significant cost. For sensing at long range using radar – for example, for stand-off ISR – the power and aperture size required limits such sensors to being carried by fairly large, complex and expensive airframes such as the RQ-4 Global Hawk, most of which are not survivable in contested airspace.

Passive radars and electronic and signals intelligence (ELINT/SIGINT) sensors require significantly less power to operate than active radars and can often be mounted in more flexible ways to suit different airframe configurations. However, they still require the capacity to conduct complex signal analysis and processing

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[36] Author testing of UAS suppression techniques, US, October 2022.

[37] *Radartutorial.eu*, 'Waves and Frequency Ranges', <https://www.radartutorial.eu/07.waves/Waves%20and%20Frequency%20Ranges.en.html>, accessed 2 February 2024.

[38] For more on synthetic aperture radar, see J Patrick Fitch, *Synthetic Aperture Radar* (London: Springer Verlag, 1988).

[39] See, for example, Missile Defense Project, 'Brimstone', *Missile Threat*, Center for Strategic and International Studies, 6 December 2017, last modified 30 July 2021, <https://missilethreat.csis.org/missile/brimstone/>, accessed 2 February 2024.

functions on the platform, or the ability to pass the raw returns data back to a ground station or other airborne asset for offboard exploitation and processing. This ensures that a capable passive radar or ELINT/SIGINT sensor payload requirement will increase the SWAP-C, cost and complexity for a given system well beyond those of an EO/IR sensor.

Finally, it is worth mentioning lasers as a joint sensor/effector capability. Lasers are most commonly employed for precise ranging, for designation of targets for strikes with laser-guided weapons, and increasingly, for directional, high-bandwidth line-of-sight communications. They are generally incorporated into an EO/IR sensor as an additional component within the optics, but generate additional requirements for power and cooling when in operation.[40] They also entail additional cost, since EO/IR sensors that incorporate a laser designator/rangefinder are more expensive and larger than basic cameras, and come with additional stabilisation and tracking requirements. There is also a processing demand generated by the logic that aligns the laser.

Effectors

There is little point in building a mass precision strike complex without the ability to deliver suitable effectors to the target area. Effectors are divided into two primary categories: kinetic; and non-kinetic. For kinetic effectors, there are three primary classes of warhead.

The first of these are general-purpose warheads that rely on a combination of high-explosive blast and fragmentation effects to kill personnel and damage structures. HE-FRAG-type warheads have lethality that scales linearly with size against soft targets such as unarmoured vehicles, personnel and civilian structures. For small multi-copter UAVs, HE-FRAG payloads are roughly the size of a hand grenade and have a lethal radius of several metres, but offer little destructive effect against buildings.[41] They can be effective against vehicles, but only if delivered accurately into hatches or on to fuel tanks or ammunition. Meanwhile, a roughly 200 kg OWA UAV such as a Shahed-136 can carry a warhead of up to 50.2 kg of various types, including thermobaric payloads.[42] This can have destructive effects against non-hardened buildings and offers a lethal radius

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[40] See, for example, Justin Bronk, ‘Production-Standard Laser Air Defense Weapons to Equip Army this Year’, *The Warzone*, 13 July 2022, <https://www.thedrive.com/the-war-zone/sponsored-content/production-standard-laser-air-defense-weapons-to-equip-army-this-year>, accessed 2 February 2024.

[41] Author visits to Ukrainian UAV training facilities and interviews with frontline operators, Ukraine, July 2023.

[42] Author examination of captured Shahed-136 airframes and observation of Shahed-136 strike impacts and blast damage, Ukraine, October 2022.

of tens of metres and the ability to reliably damage lightly armoured vehicles with near misses.

The second major category of kinetic effectors are shaped-charge warheads designed for anti-armour use. These use a small explosive charge to project a focused jet of molten copper that can penetrate through thick armour plating, creating red-hot fragments that kill crew and ignite fuel or ammunition stored inside a vehicle. These types of effectors are also known as explosively formed penetrators, or EFPs. Shaped charges enable relatively light warheads to destroy well-protected armoured vehicles, including main battle tanks (MBTs), if they hit the right sections at a relatively flat angle. In Ukraine, these effectors have been demonstrated by the large-scale use of small first-person view (FPV) racing quadcopters fitted with modified 2 kg RPG-7 warheads as short-ranged OWA UAVs.[43] The downside of shaped-charge warheads is that they have very limited blast and fragmentation effects compared with simple HE-FRAG warheads, rendering them less effective against personnel or buildings for a given weight of explosive. They are also more expensive. A specialised subset of shaped-charge warheads are two-stage warheads: some of these combine an initial charge designed to penetrate either armour or buried structures with a follow-on HE-FRAG charge that bursts inside, while in others, the primary charge is designed to set off reactive armour in order to enable a second shaped charge to defeat the main armour of well-protected modern armoured vehicles.[44] These are more complex, and thus more expensive, than single-stage shaped-charge warheads.

The third type of kinetic effectors are multirole warheads. These are increasingly common on high-end missiles and loitering munitions that need to be able to destroy a wide range of different targets. Such weapons typically use a dual-stage design, with a penetrating shaped charge as a primary stage and a compact HE-FRAG second stage. These warheads have much in common with two-stage penetrating warheads but are conceptually designed with anti-armour/anti-personnel/anti-structure mission flexibility in mind, rather than the ability to specifically penetrate either buried structures or vehicles protected by reactive armour layers. Like two-stage warheads, they are much more expensive than either HE-FRAG or single-stage shaped-charge warheads and are used when the economies of scale of ordering large volumes of a single multipurpose weapon are perceived to outweigh the additional cost of the warhead itself. The latter relationship is important to understand when examining the multirole utility of a mass precision strike capability. The requirement to be used en masse and

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[43] Author visits to Ukrainian UAV training facilities and interviews with frontline operators, Ukraine, July 2023.

[44] See, for example, Rosoboronexport, 'PG-7VR: Anti-tank Rocket', <http://roe.ru/eng/catalog/land-forces/strelkovoe-oruzhie/grenade-launchers/pg-7vr/>, accessed 2 February 2024.

thus be affordable conflicts directly with the very significant warhead costs per platform associated with true multitarget flexibility. Multirole warheads also necessarily have a lesser effect on most individual target sets than an appropriate single-role warhead of the same weight. Therefore, for small UAVs or other payload-constrained systems, the additional warhead weight for a given explosive or penetrating effect of designing a single warhead with multitarget flexibility may impose an unacceptable trade-off against fuel/battery capacity and range.

Non-kinetic effectors are, largely, EW payloads designed to degrade hostile sensors, either through noise jamming or through more sophisticated signal timing manipulation or protocol-based electronic attack techniques.[45] The advantage of deploying such payloads forward into hostile terrain on UAVs is that the physics governing radar and communications signals mean that effective jamming requires greatly diminished power input the closer the emitter can be placed to the target receiver, and the better it can be aligned to the centre of the target sensor array. The drawbacks of EW payloads are that they are more complex and expensive than kinetic warheads, require significant onboard power generation and cooling to operate for any sustained period, and rely on up-to-date mission data files and signal coding to be effective. They may still be relatively efficient and effective for larger systems being used as part of, for example, a suppression of enemy air defences campaign, where the alternatives are cruise missiles. However, EW payloads tend to be much more expensive than most kinetic effectors used in UAVs in support of the land fight. This constrains their use to complex and survivable platforms, and means that their effectiveness against hostile sensors will diminish rapidly in any conflict once used, as the enemy adapts its countermeasures to nullify the jamming. Therefore, while the airframe to carry an EW payload could be made relatively cheaply, the payloads themselves will be not only expensive but also sensitive. Furthermore, such payloads are reliant on a complex and expensive national ELINT/SIGINT collection, analysis and mission data file generation apparatus to create and rapidly update the signals that they use.[46]

Regulation

Although not part of the core design trade-offs in a UAV as a platform, regulation has an outsized impact on design choices and whether the system that produces UAVs is fit for purpose. Because early UAVs were predominantly large airframes

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45. S Barreto, A Suresh and J-Y Le Boudec, ‘Cyber-attack on Packet-based Time Synchronization Protocols: The Undetectable Delay Box’, *2016 IEEE International Instrumentation and Measurement Technology Conference Proceedings*, Taipei, Taiwan, 2016, pp. 1–6.
46. Thomas Withington, ‘Manoeuvre Warfare and the Electromagnetic Spectrum’, *RUSI Journal* (Vol. 168, No. 6, 2023), pp. 32–41.

with significant range and endurance, the certification of UAVs developed from the process that regulates aircraft. As the speed of UAV development accelerates, in terms of alterations to payload configuration, navigational logic, command link resilience and airframe, the assurance work needed to guarantee that a UAV will reliably function without crashing or deviating from its anticipated behaviour increases. Assurance of the system's reliability not only imposes time on the development process but also expands the platform cost, both to conduct the trials and to take on the risk of designing a UAV that may not be certified, thereby delaying the sequencing of design and investment in production capacity. There is, therefore, a trade-off between safety and cost.

Another consideration is regulation's indirect impact on doctrine. Safety has often imposed strict airspace management on how UAVs are integrated into exercises. The greater these constraints, however, the less realistic is the use of UAVs during training compared with their actual employment on the battlefield. Since organisations will shape themselves to solve the problems they encounter as regards novel technology, it follows that communications procedures, command relationships and other structural components of a mass precision complex will be heavily shaped by how regulation allows UAVs to be employed on exercise. The level of risk a state is prepared to accept as regards air safety in order to enable realistic training will therefore determine the extent to which UAV formations will need to be restructured in war.

A final point about regulation concerns targeting. Many of the methods for making strike UAVs more robust involve the use of autonomous target recognition. Even for ISR UAVs, object recognition is a valuable means of accelerating the targeting cycle. In principle, anti-tank mines, anti-radiation missiles and missiles with active seekers such as Brimstone are all autonomous weapons. The novelty of this should not be overstated. However, the capacity for UAVs to fly significant distances in different directions introduces safety considerations for autonomy that are more easily mitigated with older weapons. Furthermore, declarations that states expect a 'human in the loop' impose very significant constraints upon how UAVs can function. The regulation of data, assurance, and the algorithms that process the data all impose cost and time restrictions on the adaptability of UAVs. These processes therefore have tangible military consequences, especially if they are underpinned by international agreements or law, rather than policy that can be adapted in the event of war.

The various components that make up a UAV, outlined above, highlight how there are significant trade-offs involved in designing a UAV for a given mission. There is also the challenge of scaling a capability that may have a limited period of maximum utility before the adversary can map its characteristics and field hard counters. Furthermore, many of the constraints outlined above demonstrate why endeavouring to do too much with a UAV either risks preventing it from being fielded at scale or actually increases its vulnerability. Yet UAVs that are not sophisticated will often struggle to sustain the delivery of effects in the way that traditional strike systems can. This places a premium on the ability to align UAV designs to their tasks, and taking a ruthless approach to simplifying the platform. It is this matching of capabilities to tasks that is covered in the next chapter.

II. Assembling the Complex

Having considered the trade-offs in UAV design, it becomes possible to outline the key mission sets that different components of a mass precision strike complex may be designed to carry out in support of land operations. In turn, analysis of these tasks can help determine the cost, complexity, volume and parameters of the UAVs required to deliver these missions.

Mission Sets

To be worth investing in at scale, a mass precision strike complex must deliver precision effects against a sufficient volume of targets to disrupt or degrade the enemy's capacity to competitively fight. This task may be broken down into five mission sets.

The first mission set is ISR in the close fight, over the battlespace occupied by an equivalent echelon to the formation in contact. The requirement is to provide tactical formations with persistent visibility of the battlespace in order to coordinate traditional fires, or to call in mass precision strikes on identified targets. Density of sensor coverage is a key driver of capability here, as is the ability for these assets to operate from tactical formations without absorbing disproportionate cognitive load from a section or platoon. As these systems must operate persistently, little can be done to shape or route-plan where they will operate. Consequently, they will be required to fly in heavily contested airspace without shaping effects being sequenced to reduce threats prior to launch. It must therefore be assumed that these platforms will be lost in large numbers.

The second mission set is to deliver precision strikes in volume in the close. This primarily involves strikes on groups of armoured fighting vehicles, firing positions, and communications equipment. The number of targets for a strike will vary, but could number as many as 12 platforms. Range requirements likely sit at up to 10 km of depth from the forward line of own troops (FLOT), requiring an effective range of approximately 20 to 30 km to be able to launch from a safe distance behind the FLOT and cover a sufficient arc of battlespace. Targets are highly likely to be mobile and time-sensitive.

The third mission set comprises over-the-horizon reconnaissance against targets in the deep battle area. The range requirement would cover the enemy's close-support artillery and reconnaissance-fires system, requiring approximately 80 km to be traversed from point of launch. Maximum penetration range is likely constrained by transit speed as much as fuel, since beyond a certain distance many longer-range effectors will no longer be able to reliably reach targets before they have displaced. Static targets, identifiable by other means of detection such as geospatial or electromagnetic reconnaissance, are not the primary targets for these systems. Instead, the object is to precisely locate enemy artillery, air defence, and command and control infrastructure.

The fourth mission set comprises long-range strikes against operationally significant targets. Ranges may be up to 500 km, and targets could include tactical systems or fixed targets such as airfields or occupied structures of military utility. Owing to limitations on the weight that can be carried such distances by systems cheap enough to be used en masse, targets are unlikely to include hardened infrastructure, which would remain the preserve of larger and more expensive cruise and ballistic missiles. Given the long transit time implied by travelling so far from the point of launch, long-range strikes in this fourth mission set would require careful mission planning and would not involve dynamic targets. However, by offering a persistent threat of precision strike against logistical infrastructure and command and control elements, these capabilities would add significant friction to the enemy's ability to resupply and coordinate forces, and therefore to achieve concentration. These capabilities also represent a concern for air and naval forces insofar as they threaten infrastructure and basing. The planning involved means that strikes will prioritise operationally significant and therefore defended targets.

The final mission set comprises enablement of joint strike. This could be by providing airborne communications relays for other UAVs. It could also involve the delivery of loitering EW effects to degrade defences and enable them to be bypassed by more capable strike systems. A key variable in the design of such enablers is the speed of engagement for the strike that is being enabled, since this will determine the duration that the effector will need to be on target and the time it has to reach that point. Without a complicated kill chain, it may also require commonality of launch platform with the effector that the platform is enabling, and such commonality is not guaranteed. For example, penetration aids dispensed by cruise missiles will quickly be left behind by the munition. A UAV loitering over defensive systems, by contrast, can present defensive radar with a persistent variety of false targets throughout the duration of a cruise missile engagement, increasing the probability of a successful strike.

Close ISR

The core mission for close ISR is to provide persistent and widespread coverage for units in the close fight. Units that have uncompetitive situational awareness are liable to suffer disproportionately in engagements.[47] The rough requirement is for each platoon to be able to generate two UAVs.[48] The platforms must be attritable because they are needed in a confined battlespace and are required to fly irrespective of the level of EW interference – this means that they will be lost in large numbers. Since the operator cannot select the time and place of their use, and because many of them are needed, the platforms must be as cheap and simple to operate as possible, as well as having a low logistical burden.

A rotary system is the most efficient design. Since the system will likely need to be carried by dismounted personnel, a target weight below 2 kg is optimal. The platform must be usable during the day and at night, and able to identify targets in cover, meaning that a thermal optic is highly desirable – this is likely to be the most expensive component of the UAV, followed by its antenna and battery. Overall, the target price is likely to be below $2,500 per airframe, in order to enable militaries to procure the UAVs in sufficiently large numbers for training and operations as disposable assets akin to munitions. Some units that anticipate operating with a lower signature and which need greater environmental assurance will likely see the price point for their UAVs rise to $8,000 per unit. The rough flight requirements are for 40 minutes' endurance and an operating range of approximately 10 km. The cost target required to sustainably field these systems as expendable massed assets imposes limitations in terms of being able to incorporate EW resilience and non-GPS-dependent navigation and other features discussed in Chapter I. To make investing in more expensive systems affordable, the anticipated attrition rates and thus numbers required would need to be commensurately lower. Large-scale, as opposed to ad hoc, procurement may help drive prices down, thanks to economies of scale that allow vendors to manufacture more cost effectively, but this approach also makes rapid design iteration to stay ahead of enemy adaptation more difficult. One of the simplest means of increasing survivability is to make sure that the UAV utilises a different control frequency for each flight, thus requiring the adversary to identify the frequency before its EW can attack the system.

Command and control for such a system must be hands-off, because the operator is liable to be distracted by threats to their person. The platform requires the

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[47] Author interviews with Armed Forces of Ukraine General Staff, operational groups of force commanders and frontline troops, Ukraine, June, August and October 2022, May, July and October 2023, and February 2024.

[48] The reason for this is that it is often necessary to stagger launches in order to prevent breaks in coverage.

ability to maintain its position, likely by fixing itself above a visually identified point on the ground. The presumption should be that the platform is able to operate without GPS, as this will be routinely denied. The best means of achieving this is probably for the platform to measure its distance and bearing from the control station, certified as genuine through a mission-specific pre-loaded encryption key. Commands can thereafter be given to the system to move a specified distance in three dimensions, or to fly under direct control. The determination of locations of detected objects would likely be achieved by the operator based on alignment of the images with their own map. Given the need to keep the cost of the platform to a minimum, object recognition and other AI-enabled capabilities would likely be cost-prohibitive on these platforms. The optimal behaviour of the UAV if it were to lose connectivity for a sustained period would be to fly towards its last-detected direction of certified command for a comparable distance to the assessed range to the emitter, and then land.

At present there is no competitive alternative to the products of DJI, the Chinese manufacturer that dominates the market in small civilian uncrewed aerial systems (UAS). Comparable products are manufactured by NATO members, but not at a competitive price for quality. The basic reason for this is that because DJI has cornered the global civilian market,[49] it has economies of scale in production that reduce its prices – as well as having had heavy financial support from the Chinese government. In this way, NATO's civilian market is directly subsidising the development of People's Liberation Army military systems. To compete, NATO members must first increase the order volumes on a smaller selection of UAVs and enable the progressive refinement of designs. Second, it is necessary to allow sale of simplified products but with substantial parts commonality on the civilian market. Systems produced by Western vendors must be modular in design and support upgrades of certain components such as processors, sensors and radios, in order to allow initial vendor production and military procurement ramp-up to take place without resulting in obsolete equipment too quickly, and to allow for a fast pace of innovation. Without these measures, assured Western access to the necessary production volumes of UAVs in this class at a viable price point is precarious.

Close Strike

The core of this mission set is to provide the joint force with a means to degrade the fighting effectiveness and ideally halt the movement of hostile forces before they can close to within direct-fire weapons range of friendly forces. This could

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[49] Nessa Anwar, 'World's Largest Drone Maker is Unfazed — Even if it's Blacklisted by the U.S.', *CNBC*, 7 February 2023.

be achieved by destroying significant numbers of either key enablers in depth; close-support artillery and other support platforms such as vehicles extending electronic protection to advancing forces; or manoeuvre elements. Since movement of effective fighting formations over tens of kilometres tends to be vehicle dependent, most of the key target sets that must be struck to accomplish this task will be armoured vehicles. This class of massed strike assets is more likely to be required to launch on detection of targets, rather than loiter for extended periods. This is because the mission requires a large number of weapons to arrive in a short period of time, to rapidly degrade formations as they advance and to overwhelm point defence systems. It is also because the armoured nature of many key targets, particularly hostile MBTs, means that a shaped-charge warhead must be carried.

To degrade the effectiveness and/or stall the advance of enemy formations, catastrophic kills on vehicles are unnecessary; damage sufficient to immobilise a majority of the vehicles present should suffice. Combat experience in Ukraine suggests that this level of damage is reliably achievable with relatively light and cheap massed OWA UAVs such as the Russian Lancet-3M with a 5 kg shaped-charge warhead.[50] Once vehicles have been damaged sufficiently by hits to their engines, running gear or other key components, they will become stationary targets for artillery or other less specialised massed fires components such as FPV drones. Thus, in conjunction with other capabilities, the critical task for mass precision strike effects in the close is to be able to immobilise most of the tanks and armoured fighting vehicles in a hostile company-sized formation before they can close to within direct-fire range (approximately 2.5 km away from the FLOT). If this can be achieved in a manner that is significantly more cost effective and efficient than massed artillery or attack aviation, then it is likely to represent a compelling investment case.

A standard Russian tank company in a battalion has 10 MBTs, while a standard motor rifle company has between two and four MBTs and between six and eight infantry fighting vehicles or armoured personnel carriers. Therefore, as a planning assumption, stopping a company-sized assault requires the ability to reliably immobilise or otherwise mission-kill four to six armoured vehicles, which are often equipped with explosive reactive armour. The number of precision effectors required will depend on the terminal survivability of the weapon, the effectiveness of the warhead, and the accuracy and robustness of the weapon's guidance/control system. Increasing the speed of flight by using a small turbojet rather than a propeller will increase response times between launch and impact, and potentially make the weapon harder to intercept, but will increase cost and

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[50] Author interviews with Ukrainian commanders and technical specialists, and inspection of a Lancet-3 and damage inflicted on vehicles by its impact, Ukraine, July and August 2023.

thus reduce the number that can be procured and launched for a given budget; it will also reduce terminal manoeuvrability. The same can be said for warhead effectiveness – a larger or tandem warhead will give greater probability of mission-killing an armoured vehicle for each hit, but it will also necessitate a larger, more powerful airframe/propulsion configuration, which will increase cost and thus reduce affordable mass of munitions.

To give a sense of the cost boundaries, an FPV UAV with an anti-tank grenade attached to it may have a unit price of approximately $800 to $1,800.[51] However, operational data from Ukraine demonstrates that only approximately one in five of these munitions reaches a target, because of the manufacturing quality and reliability, the pilot skills required and the effect of EW on their control channels.[52] Indeed, there are large parts of the day when EW means that FPVs simply cannot be used. FPVs also have an unreliable effect on armoured targets, requiring multiple hits to kill. Moreover, because of their short range – made even shorter in cold temperatures – and the problems associated with spectrum crowding in cheap FPVs due to simple, low-quality radios, it is difficult to concentrate FPVs. Ukrainian FPV teams often need to disperse 500 m apart to avoid spectrum interference.[53] There are more advanced FPV systems emerging, which are more reliable and have higher hit ratios, but cost in the region of $3,000. FPVs nevertheless remain tools that are primarily effective when the enemy decides to accept the risk from them by turning off jamming. They are a useful section-level tool, able to deliver precise effects from cover, but are not a sufficiently reliable system to form a core capability in a mass precision strike complex.

For a weapon such as the Lancet-3M, which has a fairly reliable effect on targets that are not protected by reactive armour, and is guided by a cheap FPV control system that operates on a dual frequency and a reserve frequency to complicate jamming, the destruction of the target might be reasonably accomplished by launching between two and three weapons per target. With object designation allowing for autonomous terminal homing, the Lancet-3M can also reduce its vulnerability to interference once it is descending upon its target. With a range of approximately 35 km, Lancets can converge from multiple axes, and their size allows them to carry an antenna to interface with relay UAVs that significantly complicate attempts to jam their control frequencies. Thus, to stop a company-

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[51] The quality of an FPV will determine its price, with commercial racing drones ranging from $400 to $2,500. Additional battery packs or specialised rotors also increase price. Munitions are difficult to cost precisely, because unit costs depend upon the volume bought and the market in which they are procured. Prices for an RPG round, however, vary from $100 to $500: see The Tiger, 'RPG-7: Anti-Tank Rocket Launcher', *Military Today*, <https://www.militarytoday.com/firearms/rpg_7.htm>, accessed 4 January 2024.

[52] Author interviews with Armed Forces of Ukraine General Staff, Ukraine, November 2023.

[53] Author interviews with deputy brigade commander and command staff, Orikhiv operating area, Ukraine, February 2024.

strength Russian formation with around 10 armoured vehicles, the launch of 20 Lancet-3M type effectors should be enough. Given a publicly available cost estimate for a Lancet-3M of $30,000,[54] on munitions expenditure alone, this would suggest a cost of around $600,000 to achieve the mission.

For comparison, the US-made FGM-148 Javelin has a cost per missile of around $170,000,[55] with a range of between 1,200 m and 4,000 m depending on conditions,[56] while the AGM-179 Joint Air-to-Ground Missile (JAGM) is being offered to the British Army's AH-64E Apache fleet at up to $319,000 per missile.[57] In practice, the price of the JAGM is likely to be closer to $200,000. The cost of these two weapons reflects their additional speed, range, terminal accuracy and warhead complexity, giving them a probability of kill that is close to one, even against heavily armoured targets, though there are bespoke countermeasures that can be used to reduce this. A Lancet-style munition with a warhead comparable to a dedicated air-to-ground missile, a rocket motor to complicate interception and a more robust command link is technically feasible; however, such a design would be similar to the existing Israeli SPIKE NLOS anti-tank missile, reaching a price point of around $200,000 if it is to have comparable range.[58]

Outlining these cost point and capability benchmarks is important, because the public discourse surrounding UAVs often takes its cost assumptions from FPVs, but ascribes to them the capabilities of a Lancet, with the further enhancements of networked AI. This is unrealistic. Operational analysis is clear that while FPVs are a useful infantry weapon and additional tool, they are not reliable or dependable, and their effects do not currently scale. Moreover, a more capable UAV in the price range of existing air-to-ground missiles is likely rather redundant. However, Lancet-style UAVs deliver air-to-ground-missile-like effects at much greater range. They are easier to counter, but flexible enough to be employed when the necessary countermeasures are not in place. They are also a large enough munition to be upgraded with some modularity. The aim, therefore, should be for a munition with around 30 km range, carrying a 5 kg warhead, manufactured at a price point below $40,000 per unit.

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[54] According to documentation from Zala Aerogroup, the UAV's manufacturer.

[55] US Department of the Navy, 'Department of Defense Fiscal Year (FY) 2024 Budget Estimates: Navy: Justification Book Vol. 1 of 1: Procurement, Marine Corps', March 2023, p. xii, <https://www.secnav.navy.mil/fmc/fmb/Documents/24pres/PMC_Book.pdf>, accessed 4 January 2024.

[56] Author interviews with Javelin operators and Armed Forces of Ukraine General Staff, Ukraine, May 2022.

[57] *Aviation Week*, 'UK Approved for JAGM Purchase to Equip Apache Helicopters', 24 October 2023, <https://aviationweek.com/defense-space/missile-defense-weapons/uk-approved-jagm-purchase-equip-apache-helicopters>, accessed 4 January 2024.

[58] US Department of the Army, 'Department of Defense Fiscal Year (FY) 2021 Budget Estimates: Army: Justification Book of Missile Procurement, Army', February 2020, pp. 61–62, <https://www.asafm.army.mil/Portals/72/Documents/BudgetMaterial/2021/Base%20Budget/Procurement/MSLS_FY_2021_PB_Missile_Procurement_Army.pdf>, accessed 4 January 2024.

Deep ISR

The ability to fly and loiter in depth requires an airframe with a fixed wing and an endurance, with its necessary payload, of approximately 2.5 hours. If we assume a minimum 30-minute loiter time in the target area to identify relevant targets at a maximum depth of 70 km – determined by the maximum range of effectors available in quantity – then this would leave 120 minutes to cover up to 90 km of battlespace, including the distance behind the FLOT from which the platform is launched. If the system is to remain capable of this in moderate-to-high winds of 25 knots gusting 40 knots, with an assumption that this may be a headwind, and that the benefit of the tailwind on the return flight is taken to maintain the loiter, this requires the platform to be able to cover approximately 250 km of distance in 120 minutes, producing a target airspeed of 125 km/h. Smaller platforms may be suitable for supporting tube artillery units, given their limited range, but this constitutes a reasonable maximum requirement for an ISR UAV. The resultant airframe is likely to have a wingspan of approximately 4 m and be driven by a propeller, not least because it must be able to loiter efficiently at low speeds while over the target.[59]

In terms of sensors, ISR UAVs need EO/IR sensors. These must be gyro-stabilised to counteract vibration in order to be clear even when zoomed in. The platform must also have the ability to offboard information on detected targets. There is a design choice between a platform that conducts object recognition using its own sensors and offboards merely the classification and position of observed objects, as compared with one that offboards full-motion video. The former is significantly more complicated but resilient, while the latter pushes the analytical burden onto the receiver and requires a persistent link, which is targetable by adversary EW assets.

Deep ISR platforms are likely to be required to operate in a GPS-denied environment, and if they are to obtain an accurate fix on targets, they must also be able to determine the precise position of an identified object despite denial of navigational signals. The most likely method to achieve this is inertial navigation supported by periodic updates from terrain recognition working from pre-loaded maps. This could be overlaid with an updated calibration from a control station using an elevated narrow-beam transmission. Offboarding data would most reliably be achieved via satellite link, or a directional antenna using a software-defined radio. The ability to precisely locate target objects for strikes by other assets would likely require a laser rangefinder to calculate bearing and distance from its own position in order to obtain an accurate grid reference. Some

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[59] For some of the propulsion and configuration trade-offs that lead to this conclusion, see Rennie, ‘Drone Types’.

advanced systems can calculate an accurate position of a camera impact point using high-fidelity terrain maps, slant range calculations and terrain feature matching – however, these capabilities depend on relatively complex components on the UAV to provide it with the required onboard data points. A target located by a UAV using these means could then be compared with the fixed location of the visual image in identified maps for verification purposes.

The requirement to maintain coverage over areas of interest means that it would be necessary to deploy concurrent orbits, such that a unit of action of these UAVs would need to comprise three airframes. The expensive components would be the software-defined radio, the processing power to store and interrogate the pre-loaded map, and the sensor ball. Collectively, these are likely to bring a unit cost of up to $200,000 per airframe. Survivability would not just depend upon the relatively small radar cross-section of the platform and its slow flight but also on careful route planning. Persistent high-fidelity reconnaissance in this depth is not a mission that other capabilities reliably offer. Attempting to achieve similar effects with crewed rotary aviation is prohibitively risky. Furthermore, while a unit cost of $200,000 may sound expensive, it compares favourably with the kinds of air defence munitions that would be used to endeavour to intercept this class of UAV. As an enabler of reconnaissance and strike, such a capability is therefore probably the easiest to justify as a stand-alone capability, with minimal overlap with other means of collection.

There is a strong tendency with these platforms to complicate them by expanding the effects they can offer. The argument is that since the system can arrive over targets, why not enable it to prosecute them itself? The short answer is that munitions are heavy, and their carriage would significantly increase drag. The result would be a substantially larger platform and in practice this would see a spiralling increase in cost, with a corresponding decrease in survivability. This is why strike-capable UAVs with these ranges rapidly see costs rise into the millions of dollars, such as Turkey's TB2. Beyond a more favourable rate of exchange, such UAVs also begin to expose themselves more to threat systems; additionally, command and control at such depth is difficult to ensure, increasing the requirements for autonomy and further increasing cost and complexity. On balance, it usually makes sense to separate ISR from strike if the aim is to keep the airframe light and cheap, and to maximise volume of the capability at a price point that prohibits many adversary systems from risking illumination to prioritise engaging them. The separation of UAVs into task modules is a common architectural approach known as 'separation of concerns', and it delivers a more modular, resilient complex of systems that is more survivable than a monolithic module. A significant exception to this is where the UAV can carry non-kinetic payloads. Using its software-defined radio, if mounting a suitable antenna, such a UAV can collect both ELINT and SIGINT, or be a vector for electronic attack.

Modularity of payload makes this an option, but it would not be a routine mission set, not least because the effects would be bespoke. New systems are constantly being developed by NATO nations, and consequently smaller ELINT and SIGINT devices are emerging, meaning that the weight penalty of such capabilities is decreasing.

Deep Strike

The ability to reach and strike targets in strategic depth with a mass precision strike complex offers the potential to add to enemy operational-level dilemmas, and to combine a range of new effects with existing but contested air force mission sets. The transit times inherent in long-range strike over hundreds of kilometres make it impractical to target mobile assets in a dynamic way using such systems. Thus, in terms of navigation complexity, a system only has to be capable of navigating accurately to a pre-planned location. As detailed in Chapter I, there are many different approaches to this challenge, with cost and complexity increasing significantly if the system needs to be able to operate independently of GPS.

To travel hundreds of kilometres into enemy territory, systems must carry significant fuel reserves, a robust automated navigation system, and a sizeable warhead to allow them to have an effect on targets commensurate with their cost. This means that even systems optimised for cost efficiency over speed or sophistication, such as the first generations of the propeller-driven Iranian Shahed-136, cost upwards of $30,000 and weigh around 200 kg.[60] Russia has significantly hardened and upgraded the platform over several iterations, but has also brought the production cost up to around $80,000. Thus, the targets that are being attacked in strategic depth will generally be deliberately targeted according to a centralised process, rather than being selected ad hoc. Moreover, whereas tactical engagements can be rapidly exploited, effects in strategic depth generally take weeks, months or even years to have a decisive effect on an opposing state's capacity to fight.[61] All the while, defence systems and tactics will adapt, meaning that simply massing a single type of long-range strike effector is unlikely to generate decisive effects before defensive tactics evolve to mitigate

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[60] Author examination of captured Shahed-136 airframes and their internal components, Ukraine, October 2022. See also Uzi Rubin, 'Russia's Iranian-Made UAVs: A Technical Profile', *RUSI Commentary*, 13 January 2023.

[61] For a detailed examination of several such campaigns, see R Cargill Hall (ed.), *Case Studies in Strategic Bombardment*, Air Force History and Museums Programme (Washington, DC: US Government Printing Office, 1998), <https://media.defense.gov/2010/Oct/12/2001330115/-1/-1/0/AFD-101012-036.pdf>, accessed 3 February 2024.

its ability to reach targets reliably.[62] Instead, the navigation, guidance and terminal behaviour of mass long-range strike systems will need to iterate to stay ahead of hostile defence system adaptation during a campaign.

In terms of strike methodologies, the two approaches visible in Ukraine (used by both sides) are dispersed targeting with single platforms, and massed salvos to overwhelm defences at key defended sites. The mission requirements for dispersed targeting with single platforms are simple and can consequently be met with comparatively cheap effectors. With the 50 kg warheads that can be carried by affordable propeller-driven systems such as Shahed-136, accuracy to within several metres is required for reliable destructive effects on specific facilities or installations. With this accuracy, however, it is possible to supplement the destructive effects of a wider long-range strike campaign by using cheap precision strike effectors to hit targets that are not valuable enough to warrant using an expensive cruise missile or penetrating air strike, but still add to national warfighting and logistics capacity. This will force an opposing force to either spread out air defences, reducing coverage at critical sites, or accept significant attrition and/or logistics inefficiency over time.

The second strike methodology is to mass deep strike effectors with systems launched and mission planned to arrive at a more valuable and heavily defended target simultaneously. This requires complex mission planning, navigation and potentially datalink capabilities, if weapons are to coordinate their behaviour as a swarm in flight. These attributes raise unit cost, and also reduce the number of such strike operations that can be conducted in any given span of time with a given amount of resources. However, use of relatively affordable long-range precision effects en masse can present opponents with serious air defence dilemmas in terms of terminal lethality and interceptor missile consumption over time if used as part of a wider deep strike campaign alongside more traditional assets. The systems likely to be affordable at scale in a sustained way will probably not have complex radar cross-section reduction features or defensive aids suites, or be capable of complex or very high-speed terminal flight behaviour. This ensures that they are individually relatively easy to shoot down using conventional short-ranged air defence (SHORAD) systems such as Gepard, Tor or Pantsir. However, the threat that they can pose if allowed to get through to fixed logistics infrastructure, airbases, maintenance depots or other fixed nodes means that air defences must engage them. If enough arrive at once, some may get through due to defensive systems being overwhelmed or running short of ready-to-fire interceptor ammunition. If used to directly attack defensive systems, or launched alongside aerial decoys that complicate the positioning of air

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[62] The evolution of Ukraine's air defence system to counter combined attack waves of Shahed-136s alongside cruise and ballistic missiles shows how rapid the increase in defensive effectiveness against a given system and tactical concept of employment can be even under extreme pressure.

defences, such saturation attacks can also improve the mission success rates for more expensive and scarce cruise missiles or penetrating combat aircraft.

The potential of massed long-range precision strike effectors to be used as a key enabler for a wider strategic air and missile strike campaign would be greatly increased if the effectors were able to actively target air and missile defence systems. However, this requires active seekers, since most modern air defence systems are at least semi-mobile and will frequently reposition between different pre-set locations even when defending a fixed site. EO/IR seekers with sufficient processing power behind them to recognise, categorise and home in on air defence assets, or more sophisticated anti-radiation homing or millimetric radar seekers, are all technically possible additions to a long-range precision strike platform. However, all will greatly increase the cost to many times the figures associated with more basic fixed-target coordinate-attack systems such as Shahed-136. The efficient propeller or even small turbojet powerplants that can provide sufficient range in a relatively compact and affordable platform also limit the terminal survivability of such systems. Therefore, given that most Russian air defence systems are capable of intercepting much more challenging targets, such as AGM-88 HARM missiles, large numbers of propeller or jet-powered effectors would be needed to have a high probability of kill against aware air defence systems. At that point, it may become less competitive, in terms of cost, than simply investing a similar amount of money in increasing stocks of existing air-launched munitions natures designed for destruction of enemy air defences.[63] A cheaper option would be for ISR UAVs to designate targets for terminal guidance.

Considering these trade-offs, therefore, the value of a long-range precision strike capability appears most evident either in being able to strike targets that do not in themselves justify the exposure or expenditure of more capable assets, or in how they contribute to complex strikes. In both cases, it is cheapness and simplicity that ultimately differentiate these systems, and so the target should be to design and acquire a point attack system with a unit cost below $100,000 that is sufficiently modular to allow its navigational logic to be altered and adapted to stay ahead of adversary hard counters.

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[63] For example, a capability such as the AGM-88G Advanced Anti-Radiation Guided Missile Extended Range: see Northrop Grumman, ‘Northrop Grumman’s Advanced Anti-Radiation Guided Missile Extended Range Completes Fourth Successful Missile Live Fire’, 8 December 2022, <https://news.northropgrumman.com/news/releases/northrop-grummans-advanced-anti-radiation-guided-missile-extended-range-completes-fourth-successful-missile-live-fire>, accessed 3 February 2024. See also the SPEAR 3: MBDA, ‘SPEAR’, <https://www.mbda-systems.com/product/spear/>, accessed 3 February 2024.

Enabling Effects

There are a range of enabling effects likely to form part of the requirement set for a mass precision strike complex. The most obvious of these are communications and datalink relay assets, EW effectors, and decoys. In all cases, the mission requires a platform able to carry a sophisticated electronics payload, with the requisite power and cooling to enable its operation and sufficient power and fuel to keep it airborne at the required depth for a sustained period of time. Therefore, this category of assets is likely to be larger and more expensive than precision strike in the close or even over-the-horizon ISR classes. These assets are also likely to be fixed-wing and propeller-driven to enable slow, aerodynamically efficient flight at several thousand feet in order to provide good lines of sight to the various systems they are designed to interact with.

For datalink/communications relay functions, the key parameters are likely to be endurance on station, signal transmission range and bandwidth capacity of onboard processors, and a modern digital software-defined radio suite with frequency agility to make it harder for hostile forces to degrade its functionality when the rest of the complex is operating. The payload is, therefore, likely to be significantly more valuable than the airframe and engine combination of the platform, and will represent the cost and manufacturing bottleneck for deployable numbers. However, since relay UAVs can generally operate back from the target location(s) being engaged by kinetic components of the complex, they are unlikely to be regular targets for kinetic engagements, and so are less likely to be lost in large numbers. However, the value of their payloads means that this class of UAV will need a robust automatic navigation and safe landing/recovery function to avoid being overly vulnerable to hostile electronic attack. The number of relay UAVs required, and their centrality to the functioning of a mass precision strike complex, will ultimately be determined by the level of automation built into other elements of the system. The more automated the search and strike functions of the complex are at various operational depths, the less reliance on very low-latency assured datalink connectivity there will be.

For EW effectors as part of a mass precision strike complex, platform size and power generation limitations are likely to require a stand-in approach, rather than a stand-off one. Due to the way that electromagnetic energy propagates, the closer an EW emitter is to the receiver it is attempting to jam, the less power it will require relative to the power output of the target.[64] For small UAV-type

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[64] 'Jamming-to-Signal (J/S) Ratio – Constant Power [Saturated] Jamming', in *Electronic Warfare and Radar Systems Engineering Handbook* (Washington, DC: Naval Air Warfare Centre, April 1999), <https://www.rfcafe.com/references/electrical/ew-radar-handbook/jamming-to-signal-ratio-constant-power.htm>, accessed 3 February 2024.

platforms, therefore, stand-in jamming is likely to be the only viable approach to degrading key hostile systems such as surveillance and air defence radars. This means that not only must a precision effector carry a sophisticated electronic attack payload and sufficient power and cooling to operate it for the duration that the effect is required, but it must also carry this payload some distance inside hostile airspace. The penetration distances required will vary according to which components of the mass precision strike complex the EW effector is required to enable. However, as a rule, such systems will be more complex and more expensive than a kinetic effector with a similar range, propulsion and guidance/navigation configuration. Their effects must also be carefully tailored and tested to avoid interfering with the sensors and communications elements required for the rest of the precision strike complex to function as intended, or with any other joint force elements.

Decoys carry a form of EW payload calibrated to send signals to hostile radars that make them generate false targets, thus making it harder for operators to discern and engage real ones. Just as with electronic attack assets, such payloads tend to be complex and expensive and to rely on a sophisticated national ELINT collection, analysis and mission data production capability to be effective.[65] If such decoys are also intended to mimic larger combat aircraft or cruise missile targets, then they may also require more expensive jet propulsion and specialised airframe designs to enable them to fly at speeds and altitudes that are not easily identifiable as decoy tracks by hostile radar operators. Such decoys already exist as air- and ground-launched effects, and so the application of such techniques to a more novel massed precision effects complex would need to demonstrate a more convincing operational effect for significantly less investment compared with simply purchasing additional systems such as the US-made Miniature Air-Launched Decoy family.[66]

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65. Author observation of real-time false target generation and noise jamming techniques against military radar set and related discussions, Linköping, Sweden, 6 December 2023.
66. Tyler Rogoway, 'Recent MALD-X Advanced Air Launched Decoy Test is a Much Bigger Deal Than it Sounds Like', *The Warzone*, 24 August 2018, <https://www.thedrive.com/the-war-zone/23126/recent-mald-x-advanced-air-launched-decoy-test-is-a-much-bigger-deal-than-it-sounds-like>, accessed 3 February 2024.

III. Fielding the Mass UAV Precision Complex

Having outlined the parameters of the technologies that make up a mass precision strike complex, and the platforms involved, it becomes possible to outline the units of action, enablers and structures required to deliver these platforms at a tactically relevant scale. This chapter covers, therefore, the enabling capabilities necessary to operate a mass precision complex and the requisite units of action to field the systems. The chapter thereafter addresses some of the implications of technological trends for how the complex may function collaboratively. The last section covers the question of swarming, which is endlessly theorised but rarely detailed in terms of practical scale and purpose on the battlefield.

Dependencies

One of the most fundamentally important capabilities for enabling the sustainable and effective employment of any mass precision strike complex is close-to-real-time monitoring of the electromagnetic spectrum (EMS) across the area of operations. Neither side can deny access to all parts of the EMS at all times, even if it possesses large quantities of advanced EW equipment.[67] This is because denial of the EMS also affects friendly units, and because the emissions that enable wide-area and wide-spectrum jamming are easily identified and targeted. Therefore, even an adversary with EW superiority will have to leave parts of the spectrum open for use at certain times in certain places. The same applies to friendly EW effects being employed at the strategic, operational and tactical levels – effects being employed must be understood and deconflicted with massed precision complex operations to avoid electronic fratricide. Most small UAV losses on both sides in Ukraine are caused by EW rather than kinetic defences and, for both sides, fratricide accounts for a significant proportion of those losses.[68]

Consequently, for effective mission planning and real-time command and control of a mass precision strike complex, the ability to map, interpret and respond to hostile and friendly EW effects and EMS usage in the round is a prerequisite.[69]

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[67] David Adamy, *EW 101: A First Course in Electronic Warfare* (London: Artech House, 2001).

[68] Author visits to Ukrainian UAV training facilities and interviews with frontline operators, Ukraine, July 2023.

[69] *Ibid.*

The degree of access to or denial of each band of the spectrum will vary geographically, as well as over time, due to the impact of EW asset location, geography and the altitude bands within which assets are operating. This means a requirement for granular information on the real-time use of the EMS over such a wide area that the only likely source of such data is orbital collection.[70] Hence, a core dependency for fielding a mass precision strike complex is access to high-fidelity orbital EMS monitoring assets, suitable downlink and ground stations, and a processing and dissemination architecture to interpret the data gathered and rapidly push it out to units of action on or near the frontlines. However cheap the UAVs making up a mass precision strike complex might be, this EMS monitoring, analysis, dissemination and mission planning capability is unavoidably very expensive, and is something only states can currently achieve. Much less reliable EMS mapping can be achieved from ground systems, but it will not offer a comparable breadth of high-fidelity returns. One approach to building an EMS survey for deep strike missions in the absence of space-based collection is to use a scouting UAV to conduct dynamic, real-time safe route planning for follow-on salvos, a tactic already employed by Russia with Shahed-136 variants that push EMS and telemetry data to the weapon's launch station.[71] At the same time, such planning also relies on detailed and up-to-date terrain and feature mapping to allow flight paths to take into account terrain masking, obstacle avoidance and defences.

The survivability and effectiveness of all elements of a mass precision strike complex hinge on the effectiveness or otherwise of mission planning. The aim is to maximise mission effectiveness within the capability bounds of the various component assets while minimising loss rates likely to be suffered through risk mitigation. The level of dependency on detailed mission planning increases the further the penetration distances required into contested airspace. Routes must be more detailed, exposure to defence systems is more likely and sustained, and communications challenges are more likely to be encountered between operators and assets as penetration distances increase. Furthermore, the requirement to fly further means larger, more expensive platforms whose loss is more consequential than for small, short-range UAVs.

Another important planning input is up-to-date data on the location and activity of air defence assets within potential range of the route to be flown. Some will give away their location by actively scanning with long-range radars, but others will spend most of their time in a passive state or emitting at a power level or in

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[70] Command sergeant major, US Army XVIII Corps, panel discussion with author, United States Army 2023 LANPAC Symposium & Exposition, Honolulu, Hawaii, 17 May 2023.

[71] Author inspection of the relevant antenna on Shahed-136 samples, Ukraine, February 2024.

a frequency band that makes long-range ELINT triangulation challenging.[72] Thus, accurate intelligence on the laydown of hostile air defence assets requires fusing data from multiple orbital, stand-off and stand-in assets across all domains. All this information will feed into mission planning for navigation modes, flight routing and altitude profile, reversionary courses of action, and assumptions on connectivity to assets in flight for real-time control, re-tasking and data offboarding.

AI and other less advanced automated processing tools have already made such planning far quicker and easier than it was in the past, and such advances will no doubt continue. Therefore, mission planning teams are likely over time to become significantly smaller and to require less specialised training to be capable. However, the core input data required cannot be generated by AI, so the dependency of mission planning tools on inputs such as up-to-date geospatial and EMS data will remain, regardless of how advanced the tools themselves become. This requirement also means that UAV operators need access to feeds derived from Above Secret capabilities, and so must be appropriately cleared.

One of the most striking lessons from the large-scale use of UAVs during the war in Ukraine has been the speed at which software, and sometimes hardware, must be iteratively adapted to retain operational utility. As of mid-2023, the average period of peak effectiveness for a newly deployed UAV navigation and/or control system on the battlefield was around two weeks, with degrading effectiveness over four more weeks. Between six and 12 weeks, the adversary would have gathered sufficient data on the waveforms and techniques being used to start effectively jamming and/or spoofing the system across the front.[73] If a new UAV control technique is used near to a specialised counter-UAV EW asset such as the Russian Shipovnik-Aero, then the process of enemy adaptation is significantly faster – typically around two weeks.[74] The development of AI-enabled signals analysis and EW signal development means that these timeframes for hostile adaptation against newly deployed UAV control and navigation techniques are likely to converge towards the shorter timeframe, with the primarily limitation being assurance of countermeasures and the distribution of mission data files across defensive systems.

Consequently, a mass precision strike complex will require organic software development teams. They will need to be empowered to rapidly iterate the software and signal types used for control and navigation in order to allow the

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72. For more information, see Jack Watling, Justin Bronk and Sidharth Kaushal, 'A UK Joint Methodology for Assuring Theatre Access', *RUSI Whitehall Report*, 4-22 (May 2022), pp. 8–13.
73. Author visits to Ukrainian UAV training facilities and interviews with frontline operators and technical specialists, Ukraine, July 2023; author interviews with Armed Forces of Ukraine General Staff, Ukraine, August 2022.
74. *Ibid*.

systems that the units operate to remain effective in the face of rapid and continuous adversary adaptation. It also requires the military to have the intellectual property rights to interfere with and adjust the functioning of the system. Vendors must expose more controls to their systems in order to allow lower-level adjustments through intuitive interfaces, scripting abilities and clear, comprehensive documentation. There is also a fundamental requirement for modular platforms, where adjustments can be made to airframes or sensors can be swapped out in the field by design, rather than the currently fairly monolithic design seen in most systems. In many respects, the body of a UAV is the least important part of it, with the interfaces for wings and mission systems being critical. This rapid iteration of software and control signal frequency patterns will also need to be deconflicted with concurrent friendly-force EW efforts. Just as adversary EW techniques will be constantly adapting, friendly ones will need to do the same to remain effective against adversary UAVs, sensors and communications channels. The interplay between the constant development of EW and counter-EW software is likely to be one of the defining tests for forces seeking to effectively employ mass precision strike complexes, with the side that can better integrate and deconflict these efforts having a huge advantage. Systems which cannot be upgraded post-delivery to new radio and EW-related modules will quickly become obsolete. Equally, national regulatory and certification approaches that do not adapt to enable the required rapid pace of constant experimentation and adaptation will prevent those states from remaining competitive.

Scaling Effect

Fielding a UAV is simple in technical – if not always in regulatory or acquisition – terms. In contrast, coordinating large numbers of UAVs so that strike systems arrive while an ISR UAV remains over the target, in an EW-contested environment where different systems have variable setup times and fly at different speeds, is a complex process. Having appropriate command and control links so that UAV operators can set up and plan missions for their UAVs drawing on the intelligence feeds outlined in the previous section means that employing these systems effectively is anything but simple. This section aims to outline hypothetical units of action to deliver scale of effect for the systems described in the previous chapter.

For tactical ISR, these systems are organic capabilities within combat formations, with a density of around two UAVs per platoon. They will be attrited at a constant rate and must be resupplied. The main requirement is that the detections from these systems are not held at the platoon but are classified and passed up-echelon to the battalion or brigade command post. This could be through operators indicating what they observe; it can also be achieved by patching the feeds back via satellite uplink or other rebroadcasting systems. For mounted platoons, the ability to have the feed interrogated by a processor in order to generate detections means that what is offboarded could comprise a list of objects and locations – still images or even simple text – rather than full-motion video, reducing bandwidth requirements and helping with emissions control.

Beyond tactical ISR, the mission support necessary to maintain the efficiency of, and access to, trained operators, planning tools and maintenance favours grouping multiple UAV types into formations allocated to support parts of the front. This is consistent with lessons from Ukraine, where the efficiency of UAV operations when conducted by a dedicated formation has risen from 10% up to 70% for some mission sets.[75] This is especially necessary if capabilities such as tactical strike are to scale. Although individual strikes may be called in because of detections from tactical formations, the scaling of effect requires a large salvo of strike platforms to converge simultaneously. Given the number of munitions identified in the previous chapter as optimal for immobilising a company group, we may hypothesise that a unit of action must be able to generate 24 strike UAVs simultaneously. Assuming approximate dimensions of 2 m in length and 40 cm width with folding wings, a pack of six such UAVs should be mountable on a tactical utility vehicle. A grouping of four such vehicles, each with three crew – a driver, a communicator and an operator – would make up a platoon. Operating in two pairs, this would allow peer recovery between the launch platforms, and for offset communications antennae to be established in two separate locations, helping to make the command link to the strike wave more resilient. This would also enable strike systems to converge on a target from different vectors without staggering launches. Given the need for repeat salvos, groupings of three such platoons comprising the tactical strike company of a UAV battalion would create units of action that could be assigned in support of frontages.

Deep ISR requires a different tempo of launch and recovery. Although one UAV would be used to cover a given direction, the need to maintain an orbit generates a requirement for three UAVs to constitute a unit of action, with one being recovered, one being prepared for launch or transiting to station, and one in flight at any given time. Given a two-part disassembling wing construction and detachable tail, two airframes should fit in a tactical utility vehicle. Three platforms, therefore, should fit in two vehicles, with the spare space in the second vehicle taken up with ideally two antennae and the command and control equipment for the UAVs. A crew of three per vehicle could comprise a driver/mechanic, a communicator and sensor operator, and a pilot. This would allow

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[75] Ukrainian General Staff J7 datasets of mission performance between different formations, accessed in Ukraine, February 2024.

one mechanic to prepare a UAV for launch and one to recover a UAV, while one operator and pilot pair rested or maintained communications with other force elements, and the other pilot and sensor operator focused on programming and flying a mission. Six such vehicle pairs could, therefore, generate six orbits in depth at surge, or three sustained orbits across the battlespace, comprising a deep reconnaissance company in a mass precision strike battalion, collectively surveying approximately 60 km of front.

The number of effectors for a given deep strike will vary considerably based on the target set. However, the minimum size of the strike platforms and their requirements allows units of action to be described. Assuming an effector weighing between 140 kg and 200 kg with a warhead between 20 kg and 50 kg, it is reasonable to launch between eight and 12 effectors from a containerised set of canisters on a standard military truck.[76] There is a trade-off, with folding wings allowing for more to be carried while adding some cost and complexity to the munition. In any case, a spring-based catapult in the canister allows accelerated launch. Assuming three such vehicles comprising a launch battery, with a fourth vehicle carrying tools, spare parts and communications equipment, a standard unit of action should be able to launch up to 36 munitions, with three separate launch positions. Premising the launch unit on standard military trucks helps to disguise the launchers. The cab would then require the ability to programme the route for the munitions. Each truck would be assumed to have three crew, comprising a driver, an engineer and a communications specialist. It would be assumed that the battalion would field three platoons of such launchers, forming a deep strike company.

The final two companies in a mass precision strike battalion have several important functions. First, there is a logistics company, responsible for resupplying the different elements. Along with a platoon supporting each UAV company, the logistics company would also need a platoon responsible for fabricating and fitting parts and repairing and modifying UAVs. The second company would comprise the intelligence and headquarters company. This company would require a headquarters element and an intelligence platoon responsible for liaising with wider headquarters to plan mission sets and strikes, and for plotting flight paths. It would also need a software development platoon responsible for harvesting and analysing mission data from across the formation, patching systems, updating mission data files, and designing novel algorithms to enable concepts of employment. Finally, there would be the novel effects platoon, responsible for designing enabling effects and integrating them into payloads.

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76. For footage of a launch and transport rack for multiple 200kg Shahed-136 OWA UAVs on a smaller military truck, see *Airwars*, 'A Year of the Shahed: How Iranian Drones Became a Key Tool in Russia's Arsenal', 8 September 2023, <https://airwars.org/investigation/shahed-year-russia-ukraine-iran/>, accessed 28 December 2023.

This platoon would also be responsible for employing bespoke UAVs delivering enabling effects. Thus, the full battalion constitutes five companies: a deep ISR company, a close strike company, a deep strike company, an intelligence and headquarters company, and a support company. The reason to group these capabilities is that although different elements may be assigned to various lines of effort, the need to train and certify, and the requirement for supporting enablers to persistently use UAVs, make the administrative concentration of the capabilities sensible.

Swarming and the Impact of Autonomy

There are multiple working definitions of swarming as a capability, but for the purposes of this study, the term will be used to refer to UAVs that are networked together to allow the exchange of data and coordination of behaviour in flight between four or more assets simultaneously.

Swarming capabilities are commonly touted as the most significant area of capability development in the small UAV defence sector.[77] However, the requirement to swarm introduces significant hardware and software complexity, which in turn drives cost growth and reduces the number of individual assets that can be fielded for any given budget. Massed UAV groupings, as seen regularly in light shows at civilian displays, rely on a ground control station tracking the position of all UAVs in a formation at all times and a central mission computer sending commands to each one to coordinate their movements.[78] This allows large numbers of very simple small UAVs to fly in a coordinated fashion, but it is not a practical approach for military UAVs and weapons in a contested battlespace, due to terrain masking, EW, signal range and emissions control challenges – the ground control station would be struck,[79] decapitating the whole swarm. Instead, for a mass precision strike complex to be capable of swarming tactics, the individual assets involved must have onboard sensors and low-latency datalinks that are resistant to hostile EW disruption. In addition, each asset must carry a mission computer powerful enough, and software complex enough, to fuse the information about terrain, threats and targets received from its own

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[77] For examples of recent media discussions on swarming, see David Hambling, 'The US Navy Wants Swarms of Thousands of Small Drones', *MIT Technology Review*, 24 October 2022; Sebastian Sprenger, 'Britain's Royal Air Force Chief Says Drone Swarms Ready to Crack Enemy Defenses', *Defense News*, 14 July 2022; Paul Scharre, 'Unleash the Swarm: The Future of Warfare', *War on the Rocks*, 4 March 2015.

[78] Chris Crockford, 'The Logistics of Flying a Drone Light Show', Electric Airshows, 11 May 2023, <https://www.electricairshows.com/the-logistics-of-flying-a-drone-light-show/>, accessed 3 January 2024. See also Lightnow Drone Show, 'How to Control and Make Shows', <https://www.lightnowdroneshow.com/en/drone-show>, accessed 10 March 2024.

[79] Artillery strikes using ELINT triangulation against even small single-UAV control antennae happen every day in Ukraine, and are a key planning consideration for UAV pilots. Author visits to Ukrainian UAV training facilities and interviews with frontline operators and technical specialists, Ukraine, July 2023.

sensors and those of other UAVs in the formation through datalinks, and to react to that information dynamically in real time. These capabilities are not inherently new, nor are they reliant on advances in AI or complex machine learning models. However, what the requirements for sensors, datalinks and advanced software do is raise component costs, even if used with an inherently cheap airframe/engine combination.

Furthermore, if a mass precision strike system is premised on swarming tactics for its effectiveness against its core target sets, then the number of assets required to use it in a sustained fashion will be increased, due to the need to consistently project sufficient assets into the target area to swarm. In conjunction with the increased hardware and software complexity required, this requirement to sustainably field swarming UAVs in large quantities over time means that fielding this sort of system as more than a ‘Night One’ theatre entry tool is likely to be uneconomical.

In terms of where swarming capabilities are likely to add value commensurate with the additional cost implied by their inclusion as part of a precision strike complex, the primary application will be to improve the capability to overwhelm air defence systems. The most effective way to overwhelm air defence systems is to present them with multiple simultaneous threats from different directions. This is especially effective against SHORAD systems that use automatic cannons, or directionally mounted missile racks rather than vertical-launch missile racks. Directional systems such as Gepard or Pantsir must traverse their turret in the direction of each incoming threat to engage them sequentially, which takes time, even if the air defence system’s radar or other sensors can track 360°. However, it is also important to note that mission planning can achieve this sort of effect against defences protecting fixed sites without needing assets capable of swarming behaviour. Russian attacks with Shahed-136s frequently present Ukrainian defences with this challenge by simply sequencing launches and route planning so that multiple UAVs arrive at the target area from different directions near-simultaneously.[80]

Other advantages of swarming capabilities are that they can help reduce wasted warheads by deconflicting target selection so that multiple assets do not hit the same target. However, doing so in a way that can differentiate between a target having been hit and successfully disabled versus a target having been hit ineffectively and thus requiring a repeat strike with another asset requires significantly more advanced sensor and processing capabilities than simple deconfliction. Ultimately, for target deconfliction and strike optimisation, the value added question will come down to whether the additional efficiency against defended and undefended target sets gained from functional swarming capabilities

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[80] Author interviews with Ukrainian Air Force air defence commanders, Ukraine, October 2022.

outweighs the strike weight foregone by the increase in individual asset cost and the resultant reduction in quantity.

There are some collaborative behaviours that fall short of swarming, but which may be worthwhile. A long-range mass strike using UAVs is most effective when defensive systems have minimal time to respond, and it is therefore advantageous for the UAVs to fly low; however, if there is any requirement for communications, then low-altitude flight makes it much harder to maintain a command link. This can be resolved if one UAV flies at a high altitude and acts as a relay for those below. If the relay bird is shot down, a different UAV can rise to take station. In a context without a command link, higher-altitude flight may also allow one UAV to use navigational techniques that are not possible during lower-altitude flight, such as astral navigation. In this way, periodic lifts by one UAV may allow it to reconfirm its position and then calibrate the position of other UAVs such that inertial navigation remains accurate. So long as UAVs have software-defined radios, this kind of behaviour is relatively straightforward. It is the same functionality that is built into Russian anti-ship cruise missiles, which have one loft to search for targets while the majority retain a sea-skimming profile.[81]

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81. US Army Training and Doctrine Command ODIN Database, 'P-700 Granit (SS-N-19 Shipwreck) Russian Medium-Range Anti-Ship Cruise Missile', <https://odin.tradoc.army.mil/WEG/Asset/P-700_Granit_(SS-N-19_Shipwreck)_Russian_Medium-Range_Anti-Ship_Cruise_Missile>, accessed 3 February 2024.

Conclusion

This paper has laid out the primary dependencies and variables involved in designing and fielding a mass precision strike complex using UAVs as a core part of a modern Western land force.

The primary conclusion is that there are significantly more aggressive trade-offs and costs involved in creating a massed UAV precision strike capability that can form a core part of a land force, as opposed to one that can function as a niche tool set for specific use cases. The land forces of a medium power such as the UK must be able to reliably conduct operations in a wide range of operational environments and conditions. It is no good, therefore, relying on massed precision strike effects for core capabilities if the systems that deliver those effects do not function reliably in bad weather, extreme temperatures, at night or in an EMS-contested environment. As outlined in Chapter I, it is possible to fit UAVs with sensors and navigation, mission system and airframe features that allow them to operate in such conditions. However, if those requirements are seen as essential, then said sensors, navigation suites and mission systems will themselves add significant cost to each asset, even if the airframes can be produced cheaply en masse by additive manufacturing or reliance on the civil sector. Furthermore, once expensive sensors, payloads and hardware are added, the economic case for investing in propulsion and airframe features that will enhance survivability (but further increase costs) is strengthened, since the loss of each cheap airframe will be accompanied by the loss of expensive components.

Furthermore, developing and exploiting the capabilities potentially offered by mass precision strike complexes is not simply a matter of achieving a viable cost-per-effect in specific scenarios. No investment in military forces in the modern world comes without opportunity costs, since budget and personnel resources allocated to realising the capability must be diverted from other things. In other words, the use case for mass precision strike complexes must not only be predicated on finding mission areas where they can be sustainably procured and used at scale within available funding. They must also represent a better return on investment than other weapons systems and effectors to which resources and personnel are already/could alternatively be dedicated. This must also hold true in all likely operational scenarios that the joint force might be called upon to fight in, if such capabilities are to be fielded at scale as a core force element.

Advances in AI and software development are radically reducing the cost of achieving various levels of capability in terms of mission planning, mission systems and sensor exploitation. However, these advances come with their own – sometimes onerous – hardware and onboard power requirements, and they do not change core trade-offs in other areas. For instance, battery and fuel energy storage density is not increasing at a rapid enough rate over time to radically alter the core relationship between a platform's size and its potential range, endurance, transit speed and payload capacity.[82]

One enduring debate regarding UAVs is the extent to which they should be operated by a specialist community, as opposed to being distributed widely. The conclusion of this study is that UAVs may be distributed to provide units with situational awareness, but mass precision strike should be managed by a specialist formation. This is not only because of the significant improvement in effectiveness achievable with skilled mission planning. Experience from contemporary theatres shows that almost all UAV capabilities are highly susceptible to hard counters as the adversary learns how the UAV functions; capabilities must therefore be continuously adapted and their supporting mission data files updated. This requires scarce skills such as UAV design and programming and the accumulation of data centrally. It therefore makes sense to concentrate UAV operation if UAVs are parts of a mass precision strike complex.

While this paper has argued that there are limitations on mass precision strike efficiency when compared with legacy strike systems, it has demonstrated that against targets that lack proper defences, UAVs offer a means to achieve extremely disproportionate attrition. If they are cheap, UAVs can also impose substantial inefficiency on enemy logistics and enablement. It follows that forces are likely to endeavour to field counter-UAV capabilities, which, like mass precision strike capabilities, impose an opportunity cost on the force. Since the UAVs making up a mass precision strike complex are also available to potential state adversaries and non-state armed groups, Western militaries will need to develop and field counter-UAV and integrated air defence capabilities at scale. This paper has not addressed how counter-UAV capabilities are to be fielded. The development of counter-UAV capability will be the subject of the second study in this project.

A final observation that arises from this paper is that most NATO states lack the regulatory structures to be able to field and maintain a competitive mass UAV precision strike complex. This paper has demonstrated what features and capabilities can be used to make UAVs survivable and able to achieve their mission, but almost all techniques are contestable. In this context, preserving the effects deliverable at scale through UAVs over the course of the fight requires constant updates, the adjustment of tactics, techniques and procedures, airframe and payload optimisation and software changes. In Ukraine, this process can,

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[82] *Process Systems*, 'How Battery Technology is Slowing Down the Tech World', <https://www.valvesonline.com.au/blog/our-blog/how-battery-technology-is-slowing-down-the-tech-wo/>, accessed 3 February 2024.

at its most intense, take place in 48-hour cycles.[83] Since most NATO members treat UAVs as aircraft and therefore require their re-certification whenever they are modified if they are to be flown for testing, it follows that NATO's regulatory structures render it almost impossible to adapt the necessary capabilities at the speed of relevance. This paper, by setting out the processes required to field those capabilities, hopefully provides a realistic outline of what must be permissible if NATO forces are to retain military advantage.

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[83] Author interviews with UAV and EW operators, Ukraine, July 2023.

About the Authors

Justin Bronk is the Senior Research Fellow for Airpower and Technology in the Military Sciences team at RUSI, and Editor of the *RUSI Defence Systems* online journal. Justin also holds a Professor II position at the Royal Norwegian Air Force Academy, and is a member of the Editorial Board of the scientific and technical journal *Weapons and Equipment* at the Central Scientific Research Institute of Arms and Military Equipment of the Armed Forces of Ukraine. His PhD from King's College London examined 'Balancing Imagination and Design in British Combat Aircraft Development'. Justin is also a private light aircraft and glider pilot.

Jack Watling is the Senior Research Fellow for Land Warfare at RUSI. He works closely with the British military on the development of concepts of operation and assessments of the future operating environment, and conducts operational analysis of contemporary conflicts. Jack's PhD examined the evolution of Britain's policy responses to civil war in the early 20th century. Jack has worked extensively on Ukraine, Iraq, Yemen, Mali, Rwanda and further afield. He is a Global Fellow at the Wilson Center in Washington, DC.