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Change in the air

Disruptive Developments in Armed UAV Technology

David Hambling

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About the Author

David Hambling is a journalist and author whose work focuses on unmanned systems and other advanced technology. He writes for Aviation Week, New Scientist, The Economist, Popular Mechanics and other publications. He is based in London. His first book, "Weapons Grade" (2005), explored the military roots of consumer technology, from microwave ovens to GPS and the Internet. "Swarm Troopers: How small drones will conquer the world" (2015) examined the disruptive military potential of small unmanned aircraft. His latest book, "We: Robot" (2018,) is a wide-ranging study of commercial, industrial, social, scientific and military robots and their impact on society. Hambling has previously written papers on emerging military technology for the British American Security Council (BASIC) and the Carnegie Corporation. He holds an honours degree in Physics from Bristol University.

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Acronyms and abbreviations

CETC	China Electronics Technology Group Corporation
DARPA	US Defense Advanced Research Projects Agency
MALE UAVs	Medium-altitude, long-endurance UAVs
UAVs	Unmanned aerial vehicles

Key takeaways

- While unmanned aerial vehicles (UAVs) will not directly replace manned combat aircraft, they will steadily augment them, taking over many functions in high-intensity conflict as well as counter-insurgency operations.
- Small armed UAVs are already widespread and are being fielded in an increasing number of theatres by both small State and non-State actors.
- Small UAVs are gaining increasing levels of autonomy, providing higher capability at low cost.

Introduction

Armed unmanned aerial vehicles (UAVs) have been largely confined to operations in uncontested airspace. While States are developing large unmanned combat aircraft (commonly referred to as UCAVs) designed to operate in contested airspace, none has yet been successfully demonstrated or deployed.[1] Alongside these developments, and proceeding at a far more rapid pace, are a variety of smaller, lower-cost unmanned aircraft projects.

Box 1: Defining small UAVs

Small UAVs can be operated without the infrastructure necessary for medium-altitude, long-endurance (MALE) UAVs, without the need for runways, special hangars or refuelling facilities. They may release a guided or unguided munition or carry small arms or light weapons. Some are designed as payload-carriers which could be fitted with any of these options on a mission-by-mission basis, while also being capable of being deployed to strike a target directly with a fixed explosive, making the distinction between UAVs and loitering munitions an arbitrary one. The advent of swarming technology effectively means that the smallest of these systems will be able to operate alongside other small systems as a large single unit.

This briefing paper considers verifiable open-source material to identify disruptive developments in UAV technology, that is, those which could significantly alter the military balance. Official government statements may be of limited utility to understand the true pace of these developments, given that many military programmes have regularly failed to meet their scheduled deadlines (see box 2), and military and proprietary secrecy also limit available data. Outside of these programmes, smaller and commercial systems have advanced far more rapidly than expected. The proceeding discussion necessarily focuses on a select group of States due to their relative transparency and levels of investment in UAV technology.

Through tracing their historical development, this research brief will consider whether small armed UAVs may provide a disruptive capability far more rapidly than their larger cousins. It will identify the ongoing technological developments that will likely contribute to the capabilities of these future systems and encourage States to consider whether they will enable new military practices.

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[1] From 2010, British Defense company BAE Systems developed Taranis, "an unmanned combat aircraft system advanced technology demonstrator programme" at the cost of nearly £200 million. To date, the system has not been developed into a combat aircraft; https://www.baesystems.com/en/product/taranis. In 2014, Dassault Aviation and Airbus announced a Future Combat Aircraft System designed to "complement and eventually replace current generation Eurofighter and Rafale fighter aircraft between 2035 and 2040"; https://www.dassault-aviation.com/en/group/press/press-kits/dassault-aviation-airbus-join-forces-future-combat-air-system/.

Box 2: Resistance to robots in the US military

It is possible to identify a number of obstacles to developing certain unmanned systems. The evolution of the US Navy's MQ-25 is highly instructive. Although the original 2008 project was intended as a stealthy unmanned combat aircraft, the final version is intended to be a non-stealthy tanker and it is not scheduled for service until 2026.[2]

If successful, the development of the Chinese Dark Sword could bring about a significant change in large armed UAV capability. However, it is far from clear how far this project has progressed, and some have suggested its current capabilities may be overstated for political reasons.[3] The status of the Russian Federation's Okhotnik B stealth attack UAV remains similarly opaque.

One aspect of resistance to unmanned combat is financial. When budgets are tight, unmanned platforms compete directly for funding with manned aircraft. In the case of the United States, this led to the cancellation of the TDR-1 UAV after the Second World Ward, the later termination of the Firebee programme, and the cancellation of the QH-50 DASH unmanned helicopter in 1969.[4]

Manned aircraft programmes like the F-35 are phenomenally expensive. They are threatened if money is channelled in other directions, or if there appear to be cheaper alternatives which can fulfil the same operational requirements. Significant vested military–industrial interests may therefore contribute to ensuring that such projects continue.

A deeper cultural resistance to unmanned systems may stem from the fact that many senior US commanders are themselves former combat pilots.[5] Ex-pilots suffer from the same cognitive bias as everyone else when told that their job could be done better by a machine and this dislike is reflected in a 2007 survey which found that a third of US Air Force pilots would rather leave the service than operate an aircraft remotely.[6] Similar attitudes are likely to dominate in other military organizations where decision-making is in the hands of those who have trained as combat pilots.

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[2] B. Werner, "Navy FY 2019 Budget Request Pushes MQ-25A Stingray to Mid-2020s", USNI News, https://news.usni.org/2018/02/12/navy-fy-19-budget-pushes-back-mq-25a-stingray-purchases-to-mid-2020s.

[3] A photograph released in 2018 showed the Dark Sword development team standing in front of what might be a full-scale prototype, or simply a mockup, of the UAV. Without further verification, it is impossible to accurately assess the programme; see T. Ridgeway, "Image of China's Stealthy 'Dark Sword' Fighter-Like Combat Drone Emerges", The Drive, 5 June 2018, http://www.thedrive.com/the-war-zone/21324/image-of-chinas-stealthy-dark-sword-fighter-like-combat-drone-emerges.

[4] D. Hambling, "A Short History of the Navy's Long Dislike of Drones", Popular Mechanics, 5 February 2016, https://www.popularmechanics.com/military/weapons/news/a19306/a-short-history-of-the-navys-long-dislike-of-drones/.

[5] M. Thomson, "The Air Force's Future May Be in Drones, But Its Generals Won't Be", Time, 8 July 2013 http://nation.time.com/2013/07/08/the-air-forces-future-may-be-in-drones-but-its-generals-wont-be/

[6] T. Ricks, "Drones: AF Officer Figures There's No Way Manned Aircraft Can Keep up with Them", https://foreignpolicy.com/2014/05/09/drones-af-officer-figures-theres-no-way-manned-aircraft-can-keep-up-with-them/.

1 The rise of the small

While the military may resist machines which replace pilots, technology which helps them has historically been embraced. This includes air-launched decoys, in use since the 1950s.[7] Planners realized that these unmanned decoys would have as good a chance of survival as the manned aircraft and so could also carry a warhead.[8] This trajectory, from unarmed auxiliary to armed attack system, is likely to be followed by UAVs because they too will be effective in the role.

Modern air-launched decoys like the Miniature Air-Launched Decoy, or MALD,[9] are smaller and more capable than their predecessors. Able to fly complex routes and to carry out evasive manoeuvres, these systems are effectively single-use UAVs. These systems can carry a range of payloads. Some decoys like the MALD-J carry electronic warfare radar-jamming technology, and Raytheon has tested a version with a warhead to destroy defensive systems.[10]

The Gremlins programme of the US Defense Advanced Research Projects Agency (DARPA) takes the idea of air-launched decoys further, with a whole wave of unmanned aircraft preceding a manned strike. Gremlins differ from previous decoys in that they are re-usable—they will be recovered mid-air by a transport aircraft and can be redeployed up to 20 times. As well as confusing defenders, Gremlins could probe defences, carry out reconnaissance and potentially strike targets, either by deploying munitions or with single-use warheads.[11]

The US Air Force is also looking for an unmanned 'Loyal Wingman' to accompany manned aircraft.[12] Wingmen would be reusable, but expendable, acting as a remote sensor or launching missiles at targets indicated by the F-35 pilot. An aircraft like the BQM-167[13] might be adapted to this role. An F-35 with several Wingmen could be significantly more effective and less vulnerable than the same aircraft acting alone. In parallel, new artificial intelligence software developed for combat training is reaching the level where it could potentially outperform human pilots.[14] Such software might allow Wingmen to participate in, if not dominate, air-to-air combat.

In addition to developing the Gremlins programme, US defence company Kratos is also drawing on its experience with small unmanned jets to develop a small strike UAV for the US Air Force. This

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[7] The Quail, for example, was a jet-powered decoy 4 m long (carried by the B-52 bomber) which flew on a pre-programmed flight path at over 500 mph for an hour. Quail had a radar signature similar to the launch aircraft, drawing interceptors and missiles away; see Federation of American Scientists, "ADM-20 Quail", https://fas.org/nuke/guide/usa/bomber/adm-20.htm.

[8] An advanced decoy known as SCAD (Subsonic Cruise Armed Decoy) later evolved into the AGM-86 Air-Launched Cruise Missile; see Encyclopedia Astronautica, http://www.astronautix.com/a/agm-86a.html.

[9] Raytheon, https://www.raytheon.com/capabilities/products/mald.

[10] Raytheon has already tested a warhead that would give the MALD air vehicle the ability, when coupled with a seeker, to attack a ground target once the MALD air vehicle's fuel expires and it descends towards the ground; http://www.airforce-magazine.com/Features/newtech/Pages/Box041910mald.aspx.

[11] E. Ackerman, "DARPA's Semi-Disposable Gremlin Drones Will Fly by 2019", IEEE Spectrum, 9 May 2018, https://spectrum.ieee.org/automaton/robotics/military-robots/darpas-semidisposable-gremlin-drones-will-fly-by-2019.

[12] J. Drew, "Pentagon Touts 'Loyal Wingman' for Combat Jets", Aviation Week, 30 March 2016, https://www.flightglobal.com/news/articles/pentagon-touts-loyal-wingman-for-combat-jets-423682/.

[13] Kratos, Unmanned Systems Division, "BQM-167A", http://www.kratosusd.com/capabilities/unmanned-aerial-systems/bqm-167a.

[14] D. Hambling, "AI Pilot Helps Us Air Force with Tactics in Simulated Operations", New Scientist, 22 November 2016, https://www.newscientist.com/article/2113709-ai-pilot-helps-us-air-force-with-tactics-in-simulated-operations/.

agile unmanned aircraft is intended to carry 500 lbs of precision munitions.[15] This is a fraction of the capacity of a manned jet but will cost just $2 million rather than the $100 million of an F-35. The unmanned aircraft is described as 'attritable,' meaning losses are acceptable and expected —unlike losses of manned aircraft.

This section has focused on US developments as these have been the most visible and the cost of development means that few other States can finance such an extensive range of projects. Other States, such as Australia[16], Italy[17] and Sweden,[18] already field jet-powered target UAVs and air-launched decoys and any significant developments in the capabilities of these systems are likely to be adopted by other militaries in the future.

The comparatively low cost and rapid development time of smaller UAVs, compared to the decades-long process of producing a manned aircraft, suggests that this type is likely to evolve rapidly and proliferate widely. Such UAVs are more likely to be culturally acceptable to air force planners as they can be seen as the pilot's friend and ally rather than their replacement. Given the technological developments in the commercial sector, it is possible to envisage a future in which manned combat aircraft are accompanied by numbers of Wingmen and other unmanned auxiliaries, each of which may also launch swarms of smaller unmanned craft.

The coming swarm

Much smaller unmanned aircraft are also gaining new capabilities. In 2017 the Pentagon held an exercise in which three F/A-18 jets released 103 small Perdix UAVs.[19] The Perdix, which weigh just 300 g each, communicated with each other to effectively carry out their mission as a single unit. The 3D-printed Perdix, costing just a few hundred dollars each, could potentially probe defences, act as decoys or jammers, or gather intelligence with surveillance sensors.

The public demonstration of this novel capability may have been prompted by international competition. China has made a number of claims of its superiority in swarming technology and state-owned CETC (China Electronics Technology Group Corporation) has continued to demonstrate larger and larger swarms (see table 1).[20] The potential lethal application of this technology has also been alluded to in a promotional video which showed a swarm converging in an attack on a missile site.[21] It is worth noting in this context that China is the largest supplier of small consumer drones, which use much of the same technology.[22]

Table 1: Successive records for size of swarm of fixed-wing UAV (all military)

DATE	NUMBER OF UAV	DEVELOPER	STATE	TYPE
04-2015[23]	30	US Navy	US	Coyote
09-2015[24]	50	US Navy	US	Coyote
11-2015[25]	67	CETC	China	Skywalker
12-2015[26]	103	US DoD	US	Perdix
06-2017[27]	119	CETC	China	Skywalker
04-2018[28]	200	CETC	China	Skywalker

Controlling swarms is different to current MALE UAVs, which are flown remotely by a human pilot. Instead of being controlled directly, the swarming UAVs are largely autonomous, flying themselves and coordinating their actions to avoid collisions by using techniques similar to those found in nature.[29] This involves a simple set of rules for maintaining separation and direction, which allows the swarm to maintain cohesion as a unit. One human operator can control the entire swarm as a single entity.

As the size of UAV swarms in the commercial sector increases, they are likely to be of increasing interest to militaries. The most visible civilian application has been in the creation of flying light shows with swarms of illuminated UAVs, by companies such as Intel and Ehang (see table 2). Several States have realized the potential advantages these systems could have over traditional air defence systems, and several have established programmes dedicated to their development.

The Republic of Korea has recently announced a 'Dronebot' combat unit which will focus on small, swarming UAVs, initially for reconnaissance but potentially also for large-scale attack as a means of neutralizing DPRK missile launchers and other targets.[30] In Israel, the military research and development organization MAFAT is working on swarming software to allow large number of drones to be controlled by a single operator. This technology is expected to be fielded in the next

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[15] Kratos, "Kratos Receives Low-Cost Attritable Strike Unmanned Aerial System Demonstration Contract Award", 11 July 2016, http://ir.kratosdefense.com/news-releases/news-release-details/kratos-receives-low-cost-attritable-strike-unmanned-aerial.

[16] The Australian Navy fields the Kalkara, a pilotless high-performance remotely controlled target drone; http://www.navy.gov.au/aircraft/bae-kalkara-unmanned-aerial-target.

[17] Leonardo, http://www.leonardocompany.com/en/-/drone-mirach-bersaglio.

[18] R. Stott, "AREXIS Airborne Attack", Janes' 360, 15 September 2017, https://www.janes.com/article/74074/arexis-airborne-attack-dsei17d4.

[19] CBS News, "Capturing the Swarm", 20 August 2017, https://www.cbsnews.com/news/60-minutes-capturing-the-perdix-drone-swarm/.

[20] D. Hambling, "If Drone Swarms Are the Future, China May Be Winning", Popular Mechanics, 23 December 2016, https://www.popularmechanics.com/military/research/a24494/chinese-drones-swarms/.

[21] J. Lin and P. Singer, "China is making 1,000-UAV drone swarms now", 9 January 2018, https://www.popsci.com/china-drone-swarms#page-3

[22] For example, Chinese company DJI is estimated to have up to 75 per cent share of the US market; J. Bateman, "China Drone Maker DJI: Alone Atop the Unmanned Skies", CNBC, 1 September 2017, https://www.cnbc.com/2017/09/01/in-race-to-dominate-drone-space-west-is-no-match-for-chinas-dji.html.

[23] D. Smalley, "Low-Cost Unmanned Aerial Vehicle Swarming Technology (LOCUST)", Naval Drones, 23 May 2016, http://www.navaldrones.com/LOCUST.html.

[24] R. Bishop, "Record-Breaking Drone Swarm Sees 50 UAVs Controlled by a Single Person", Popular Mechanics, 16 September 2016, https://www.popularmechanics.com/flight/drones/news/a17371/record-breaking-drone-swarm/.

[25] D. Hambling, "If Drone Swarms Are the Future, China May Be Winning", Popular Mechanics, 23 December 2016, https://www.popularmechanics.com/military/research/a24494/chinese-drones-swarms/.

[26] K. Mizokami, "The Pentagon's Autonomous Swarming Drones Are the Most Unsettling Thing You'll See Today", Popular Mechanics, 7 January 2017, https://www.popularmechanics.com/military/aviation/a24675/pentagon-autonomous-swarming-drones/.

[27] X. Bo, "China Launches Record-Breaking Drone Swarm", Xinhua, 11 June 2017, http://www.xinhuanet.com/english/2017-06/11/c_136356850.htm.

[28] Sina News, "Unmanned Cluster Flight Set a World Record", 4 May 2018, http://news.sina.com.cn/s/2018-05-04/doc-ifzyqqiq6982537.shtml.

[29] I. Lachow, "The Upside and Downside of Swarming Drones", Bulletin of the Atomic Scientists, vol. 73, no. 2, 2017, pp. 96–101.

[30] B. Harris, "South Korea to Create 'Drone-Bot Combat Unit' to Swarm North", Financial Times, 6 December 2017, https://www.ft.com/content/6878ba90-da1a-11e7-a039-c64b1c09b482.

two years.[31] Turkey is also adding swarming capability to its Alpgau-2 small loitering munitions.[32] The US Navy's LOCUST programme—an abbreviation of Low-Cost UAV Swarming Technology—specifically aims to use large numbers to overwhelm an enemy.[33] The Russian Federation is also active in this area.[34]

Table 2: Successive records for size of swarm of rotary-wing UAV (all civil)

DATE	NUMBER OF UAV	DEVELOPER	NATION	TYPE
01-2016[35]	100	Intel	US	Shooting Star
11-2016[36]	500	Intel	US	Shooting Star
02-2017[37]	1,000	Ehang	China	Egret
01-2018[38]	1,218	Intel	US	Shooting Star
05-2018[39]	1,374	Ehang	China	Egret
07-2018[40]	2,018	Intel	US	Shooting Star

[31] Y. Stoler, "The Israeli Military Has Big Plans for Small Drones", Calcalist, 29 June 2018, https://m.calcalistech.com/Article.aspx?guid=3741316.
[32] Defence Turkey, "STM Unveiled 'Stand-Off Through the Wall Target Acquisition System' (UHTES) at 2018 Eurosatory", https://www.defenceturkey.com/tr/icerik/stm-unveiled-stand-off-through-the-wall-target-acquisition-system-uhtes-at-2018-eurosatory-3134.
[33] D. Smalley, "LOCUST: Autonomous, Swarming UAVs Fly into the Future", Office of Naval Research Communications, 14 April 2015, http://www.navy.mil/submit/display.asp?story_id=86558.
[34] TASS, "Russia is Developing Artificial Intelligence for Military and Civilian Drones", http://tass.com/defense/945950.
[35] R. Swatman, "Intel Stuns During CES Keynote with Record for Most Drones Airborne Simultaneously", Guinness World of Records, 6 January 2016, http://www.guinnessworldrecords.com/news/2016/1/intel-stuns-during-ces-keynote-with-record-for-most-drones-airborne-simultaneousl-411677.
[36] R. Swatman, "Intel Launches 500 Drones into Sky and Breaks World Record in Spectacular Style", Guinness World of Records, 4 November 2016, http://www.guinnessworldrecords.com/news/2016/11/intel-launches-500-drones-into-sky-and-breaks-world-record-in-spectacular-style-449886.
[37] E. Hang, "Watch a Record-Setting 1,000 Drones Take to the Sky in China to Celebrate the Lantern Festival", Quartz, 13 February 2017, https://qz.com/908927/watch-a-guinness-record-setting-1000-drone-show-in-guangzhou-china-celebrating-lantern-festival-and-end-of-chinese-new-year/.
[38] The Engineer, "Intel Breaks Drone Record with Olympics Display with Promise of More to Come", 12 February 2018, https://www.theengineer.co.uk/intel-drone-olympics/.
[39] S. Whiltaker, "China's Ehang Beats Intel to Break World Record With 1,374 Strong Drone Swarm", Drone Below, 3 May 2018, https://dronebelow.com/2018/05/03/chine-ehang-beats-intel-world-record-1300-drone-swarm/.
[40] Intel, "Intel Breaks Guinness World Records Title for Drone Light Shows in Celebration of 50th Anniversary", 18 July 2018, https://newsroom.intel.com/news/intel-breaks-guinness-world-records-title-drone-light-shows-celebration-50th-anniversary/.

2 The spread of small

Unlike traditional aircraft, small UAVs can be developed and deployed without a large infrastructure, making them an attractive option for small States and non-State actors. A limited number of States have the necessary support infrastructure to deploy MALE UAVs like the US Reaper, Israeli Heron or Chinese Caihong-5, but consumer UAVs can be purchased relatively easily. The weaponization of consumer quadcopters by non-State armed groups has had a significant effect on the dynamics of the battlefield and State militaries are increasingly looking to adapt UAVs as lethal delivery mechanisms.

The Iraqi Federal Police started using armed quadcopters after encountering them in the hands of Daesh, which had initially used the UAVs for reconnaissance and directing mortar fire, but by 2017 were using them as a lethal delivery mechanism.[41] UAVs dropping grenades proved highly effective during the US-backed assault on Mosul in 2017. Even though the United States maintained air supremacy, the UAVs operated by Daesh—flying at just a few hundred feet—proved difficult to shoot down.[42] The attacks were only stopped when radio jammers were brought in to block communications between operators and the systems. Similar attacks are expected to spread to other theatres, with a wider variety of UAVs and in greater numbers.

In January 2018, 13 small UAVs from an unknown source carried out a mass attack on Russian forces in the Syrian Arab Republic.[43] Their main target was the Khmeimim Air Base, where grounded aircraft offered a tempting target. The UAVs were guided by GPS, and each carried 10 grenade-sized bombs which were to be released in a row to cover the maximum area and compensate for aiming errors. The large number of attackers seem to have been an attempt to overwhelm defences with numbers. The Russians claim to have shot down or jammed all the attacking drones without casualties. Even damaging one aircraft would have been a great success given that the UAVs only cost a few thousand dollars each.

The operation was attributed to non-State actors, although Russian officials claimed that a State must have provided them with assistance.[44] Small UAV attacks on Khmeimim have continued sporadically. Although their exact origin remains uncertain, the attacks have been cited as one of the reasons for the assault on Idlib.[45]

The Israeli military has made extensive use of commercial multicopters and has issued DJI Mavic consumer quadcopters to all of its infantry units.[46] Use of these systems has now also extended beyond surveillance to utilizing them as a delivery mechanism. Commercial UAVs were recently used to drop tear gas on protesters in Gaza;[47] a larger multicopter has been developed specifically to

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[41] N. Waters, "Iraqi Federal Police Using Weaponised Drones", Bellingcat, 2 March 2017, https://www.bellingcat.com/news/mena/2017/03/02/iraqi-federal-police-using-weaponised-drones/.

[42] D. Larter, "SOCOM Commander: Armed ISIS Drones Were 2016's 'Most Daunting Problem'", 16 May 2017, http://www.defensenews.com/articles/socom-commander-says-isis-drones-were-2016s-most-daunting-problem.

[43] BBC, "Syria War: Russia Thwarts Drone Attack on Hmeimim Airbase", 7 January 2018 https://www.bbc.co.uk/news/world-europe-42595184.

[44] R. Browne, "Russia Suggests U.S. May Have Had Role in Attack on Russian Bases in Syria", CNN, 10 January 2018, https://edition.cnn.com/2018/01/09/politics/russia-us-attack-base-syria/index.html.

[45] TASS, "Russia Vows to Wipe Out Terrorist-Run Drone Assembly Workshops in IDLIB", 14 September 2018, http://tass.com/politics/1021676.

[46] J. Gross, "Low-Tech Drones Give Every IDF Commander an Eye in the Sky", The Times of Israel, 20 November 2017, https://www.timesofisrael.com/low-tech-drones-give-every-idf-commander-an-eye-in-the-sky/.

[47] Times of Israel, "Israel Deploys Drones to Drop Tear Gas on Gaza Protesters", 31 March 2018, https://www.timesofisrael.com/israel-deploys-drones-to-drop-tear-gas-on-gaza-protesters.

drop a malodorant liquid known as 'Skunk',[48] and in 2015 Israel special forces used a sniper rifle mounted on a large consumer UAV to carry out a mission.[49] Since then a bespoke UAV called TIKAD has been developed for the task, which can carry a stabilized rifle, rocket launcher or other weapon depending on the situation.[50] Other improvised or semi-improvised solutions, including lethal ones, are likely to be fielded as required.

In addition to adapting commercial systems, many States with little history of developing military aircraft can now mass-produce miniature attack UAVs far more sophisticated than simple consumer multicopters. States such as Poland,[51] Turkey[52] and Belarus[53] have demonstrated a range of systems with capabilities that blur the boundary between loitering munitions and armed UAVs. One example is the Ukrainian-made 'Demon', which can be fitted with an RPG-26 anti-tank rocket launcher and be re-used, or it can carry a 5 kg explosive charge for direct attacks.[54]

Houthi forces in Yemen have used 'Qasef-1', a propeller-driven UAV with a 3 m wingspan and an explosive warhead, which can be flown by remote control or guided to a location by GPS. It is claimed to have been developed locally but a recent United Nations Panel of Experts found that the model is likely to have been an imported version of the Iranian Ababil.[55] Although denied by coalition forces, Houthi forces have also claimed to have successfully deployed swarming technology in a series of attacks.[56] This raises the prospect that the sort of swarm tactics embodied by Gremlins, Perdix or LOCUST are already being employed on a crude level by non-State armed groups.

The threat from these small UAVs is currently limited by their range. Consumer UAVs currently have a range of a few kilometres, however innovative technological developments are dramatically extending their flight time. The experimental 6 kg Swiss AtlantikSolar can fly indefinitely, running on solar power by day and batteries by night.[57] Many other projects are developing the same technology for small UAVs, such as the US Navy's Hybrid Tiger,[58] and the commercial/military Silent

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[48] C. Eisenberg, "Shoko Drone Ready to Douse Rioters in Skunk Water", Jerusalem Post, 16 May 2018, https://www.jpost.com/Israel-News/Shoko-drone-ready-to-douse-rioters-in-skunk-water-556641.
[49] D. Hambling, "When a Hobby Drone Becomes a Military Sniper", Popular Mechanics, 16 August 2017, https://www.popularmechanics.com/military/research/news/a27754/hobby-drone-sniper/.
[50] J.A. Gross, "Unmanned Subs, Sniper Drones, Gun That Won't Miss: Israel Unveils Future Weapons", Times of Israel, 5 September 2017, https://www.timesofisrael.com/unmanned-subs-and-sniper-drones-israel-unveils-its-weapons-of-the-future/.
[51] The WARMATE combat unmanned aerial vehicle (CUAV) is a multi-role system performing multiple tasks depending on the type of the head installed; WG Group "WARMATE Loitering Munitions", http://www.wbgroup.pl/en/produkt/warmate-loitering-munnitions/.
[52] A.R. Dombe, "Turkey Unveils Alpagu 2 Tactical Attack UAV", Israel Defense, 5 December 2017, http://www.israeldefense.co.il/en/node/32067.
[53] K. Atherton, "Belarus Reveals Drone That Is a Rocket Launcher with Rotors", C4ISRNET, https://www.c4isrnet.com/unmanned/2018/06/04/belarus-reveals-drone-that-is-a-rocket-launcher-with-rotors/.
[54] UAS Vision, "Grenade Launching Drone from Ukraine", https://www.uasvision.com/2018/08/20/grenade-launching-drone-from-ukraine/.
[55] Conflict Armament Research, "Iranian Technology Transfers To Yemen", March 2017 http://www.conflictarm.com/perspectives/iranian-technology-transfers-to-yemen/.
[56] South Front, "Houthis Destroyed UAE Patriot System In Central Yemen With Swarm Of Drones — Reports", 24 February 2017, https://southfront.org/houthis-destroyed-uae-patriot-system-in-central-yemen-with-swarm-of-drones-reports/.
[57] AtlantikSolar, "Research Paper on AtlantikSolar's Flight Endurance World Record Published", 6 June 2017, http://www.atlantiksolar.ethz.ch/?p=1025.
[58] G. Fein, "USN Seeks Multi-Day Flight with Hybrid Tiger", Jane's International Defence Review, 14 August 2017, http://www.janes.com/article/73060/usn-seeks-multi-day-flight-with-hybrid-tiger.

Falcon.[59] US defence officials have expressed concern that such UAVs could be readily acquired and weaponized by both State and non-State groups, raising the possibility of UAVs travelling thousands of kilometres to attack high-value targets.[60]

[59] T. Eshel, "Silent Falcon to Soar for 14 Hours Powered by Solar Energy", Defense Update, 14 August 2013, https://defense-update.com/20130814_slent_falcon.html.

[60] "In about five years, drones will be able to be launched from Africa which can reach our shores, because they'll have permanent power by the sun", warned US Assistant Secretary of Defence Owen West in 2017; C. Houck, "Trump's Special Ops Pick Says Terror Drones Might Soon Reach the US from Africa. How Worried Should We Be?", Defense One, 23 July 2017, https://www.defenseone.com/threats/2017/07/trumps-special-ops-pick-says-terror-drones-might-soon-reach-us-africa-how-worried-should-we-be/139642/.

3 Small gets smart

Technological developments will enable new capabilities in small UAVs in the future. Advances in processing technology will enable the inclusion of increasingly sophisticated artificial intelligence and greater degrees of autonomy. These developments will have significant implications, enabling small UAVs to evade existing jamming technology and potentially carry out autonomous targeting.

Developments in the commercial sector point to things to come. Deep learning technology enables smartphones to turn speech into text and allows Google's banks of servers to label billions of photos and video imagery without human assistance. The full military implications of this type of artificial intelligence are still being considered.[61]

Previously, the specialist processing chips needed to drive deep learning were too power-hungry for small UAVs. New neural network hardware brings artificial intelligence, with the potential of autonomous operation, to the smallest of them.

The Skydio R1 is an advanced consumer multicopter which can navigate terrain and track a moving subject for video recording without human oversight.[62] The R1 is equipped with NVIDIA Jetson, a processor designed to run artificial intelligence applications efficiently.[63] Most chips have only a handful of cores, the Jetson has no less than 192 processing cores to tackle the heavy-duty processing required by deep learning neural networks.

Intel also produces chip-scale neural network hardware, such as the Movidius, which is the 'brain' of the popular DJI Phantom 4. In January 2018, Intel demonstrated a palm-sized consumer quadcopter retailing at just $99 with a Movidius processor. The technology will continue to get smaller and more capable.

Qualcomm Technologies, which makes the processors in most of the world's smartphones, also offers neural hardware. Their credit-card-sized Qualcomm Flight is aimed at the UAV market. In particular it tackles the challenge of 'simultaneous location and mapping' or SLAM, where a robot creates a map of its surroundings from video imagery as it goes. SLAM allows UAVs to navigate by sight alone.[64]

SLAM is important because most UAVs rely on GPS to navigate and find their way to a target, and some jammers work by blocking the satellite navigation signal. A UAV using visual guidance can find its way just as well without satellite assistance, making such jammers ineffective. Equally importantly, SLAM will enable UAVs to find their way around the inside of buildings. The PD-100 Black Hornet used by several militaries is already advertised as being capable of operating inside structures.[65]

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[61] UNIDIR, "The Weaponization of Increasingly Autonomous Technologies: Concerns, Characteristics and Definitional Approaches", September 2017, http://www.unidir.org/files/publications/pdfs/the-weaponization-of-increasingly-autonomous-technologies-concerns-characteristics-and-definitional-approaches-en-689.pdf.

[62] Skydio, "Introducing R1", 13 February 2018, https://www.skydio.com/2018/02/introducing-r1/.

[63] NVIDIA, "The Most Advanced Platform for AI at the Edge", 16 March 2018, http://www.nvidia.co.uk/object/jetson-tk1-embedded-dev-kit-uk.html.

[64] H. Durrant-Whyte and T. Bailey, "Simultaneous Localization and Mapping: Part I," IEEE Robotics & Automation Magazine, vol. 13, no. 2, 2006, pp. 99–110.

[65] https://www.army-technology.com/projects/pd100-black-hornet-nano/.

Deep learning also allows UAVs to identify objects automatically. A number of applications of this capability have already been demonstrated in the commercial sector.[66] Similar technology could allow a small UAV to locate and identify military targets—vehicles, artillery or personnel wearing a specific uniform or carrying weapons. The US military is developing deep learning technology to enable small UAVs to locate and identify targets.[67]

Small, low-cost UAVs capable of autonomous route planning and obstacle avoidance, navigation and target identification would have tremendous military potential. Without a need for a link to a human operator they could autonomously verify and attack targets. Previously there has always been a desire by the military to maintain a 'man-in-the-loop' controlling any autonomous system. More recently this has been adapted to 'man-on-the-loop' in which a human is not directly in charge but can step in at any point. Debates about what constitutes meaningful human control continue,[68] and the legal and ethical issues around the use of lethal artificial intelligence are still very much under discussion. What is clear is that the technical potential for fully autonomous armed UAVs now exists and is proliferating.

In addition to coordinating simultaneous attacks on a single target, such UAVs could disperse to find and attack a large number of targets. As some commentators have noted, such swarms could become weapons of mass destruction—albeit unusually well-targeted ones. Stuart Russell of Berkeley describes them as 'slaughterbots' and warns that they might be used by terrorists or others to carry out large-scale massacres.[69] Swarms could be launched from a ship, carrier aircraft or even a truck from some distance away. Others raise questions over the feasibility of such large swarms, but the technical issues appear surmountable (see box 4).

A large UAV swarm could cause massive civilian casualties. Unlike nuclear, biological and chemical weapons, small UAVs are not regulated and would not require an extensive scientific research or industrial base to produce. Manufacture would be relatively hard to spot—compared to the production of traditional military hardware such as manned aircraft, ships or ballistic missiles—as it would resemble any other consumer electronics assembly.

Due to a lack of transparency, it is difficult to ascertain the extent of military research in this area. DARPA's recent demonstration of a small multicopter UAV able to autonomously navigate and find its way into and through buildings—and presumably locate targets—is an indication of the degree of sophistication already realized.[70]

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[66] The experimental Little Ripper multicopter is currently at work on Australian beaches to provide warning of sharks. The UAV itself identifies the threat, thanks to Deep Learning software called SharkSpotter which can pick out sharks from swimmers, surfboards boards and dolphins. SharkSpotter currently recognizes sixteen types of object, including swimmers, boats and rays, and does it far more reliably than a human operator—about 90 per cent compared to 30 per cent; University of Technology, Sydney, "Sharkspotter—A World First in Shark Detection", 21 April 2017, https://phys.org/news/2017-04-sharkspottera-world-shark.html.

[67] D. Hambling, "US Wants First Drones that Can Kill People Truly Independently", New Scientist, 23 March 2018, https://www.newscientist.com/article/2164710-us-wants-first-drones-that-can-kill-people-truly-independently/.

[68] UNIDIR, "The Weaponization of Increasingly Autonomous Technologies: Considering how Meaningful Human Control Might Move the Discussion Forward", 2014, http://www.unidir.org/files/publications/pdfs/considering-how-meaningful-human-control-might-move-the-discussion-forward-en-615.pdf.

[69] S. Russell, A. Aguirre, A. Conn and M. Tegmark, "Why You Should Fear 'Slaughterbots'—A Response", IEEE, 28 January 2018, https://spectrum.ieee.org/automaton/robotics/artificial-intelligence/why-you-should-fear-slaughterbots-a-response.

[70] DARPA, "Faster, Lighter, Smarter: DARPA Gives Small Autonomous Systems a Tech Boost", 18 July 2018, https://www.darpa.mil/news-events/2018-07-18.

It is possible that the civil sector is leading the way in the development of aspects of this technology. Certainly it is now well in the mainstream; the latest iPhone XS includes an A12 bionic chip with a neural engine claimed to be thousands of times faster than the previous version just a year earlier.[71] This may result in a level playing field for all States to acquire powerful disruptive technology at the same rate.

Box 3: Scaling up swarms

Operating a small number of UAVs is relatively simple, but serious practical issues arise when handling a swarm of hundreds or thousands. These issues are often understated, for example by those warning of 'slaughterbot' swarms. Preparing a thousand UAVs for launch is not a trivial task. However, there is reason to believe that the issues can be resolved with appropriate design.

The Kilobot is a non-flying, desktop robot the size of a table tennis ball, developed by researcher Michael Rubenstein and colleagues at Harvard to test swarming algorithms on real-life hardware rather than in a computer simulation.[72] The team therefore devised a low-cost machine which could be easily marshalled in large numbers.

Kilobot software is installed remotely via an infrared link, which is also used to turn the robots on and off. They are recharged en masse by placing them between charging plates. This removes the need to handle individual machines and makes the swarm scalable, so a hundred can be operated as easily as ten.

As the name suggests, Kilobots are designed so that researchers can operate a thousand of them together. Further, the construction details are open-source and freely available online for other researchers. A similar approach is likely to be adopted for swarming UAVs to overcome the difficulties of configuring, programming and charging large numbers of machines individually.

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[71] S. Shankland, "iPhone XS A12 Bionic Chip is Industry-First 7nm CPU", CNET, 12 September 2018, https://www.cnet.com/news/iphone-xs-a12-bionic-chip-is-industry-first-7nm-cpu/.

[72] M. Rubenstein, "Kilobot: A Low Cost Scalable Robot System for Collective Behaviors", IEEE International Conference on Robotics and Automation, May 2012, https://ssr.seas.harvard.edu/publications/kilobot-low-cost-scalable-robot-system-collective-behaviors.

Conclusion

Small armed UAVs show great military potential. They range from jet-powered machines weighing tons through to propeller-driven aircraft weighing tens of kilograms, down to consumer models under a kilogram able to carry improvised explosives. The technology to produce and operate them is becoming ubiquitous, and their effectiveness is greatly multiplied when deployed in swarms and with the aid of new deep learning technology.

A key aspect for all of these systems is that, unlike armed existing models, they will be used in contested air space, and in a wide range of conventional military operations, rather than simply as counter-insurgency tools.

One proposed mission for the US Air Force's planned strike UAV is 'offensive counter air'—attacking opponents air forces on the ground. The loss of a dozen such UAVs would be a good exchange for a single enemy aircraft. Strike UAVs are ideal for missions deemed too risky for human pilots, especially in 'door kicking' operations to neutralize air defences at the start of conflict. This is a contest in which attackers seek to destroy surface-to-air missile sites before they themselves are shot down. UAVs may help by finding such sites, by jamming their radar, or simply overwhelming them with numbers.

"You have maybe a hundred or a thousand surface-to-air missiles, but we're going to hit you with ten thousand [small UAVS]", Colonel Travis Burdine, the US Air Force's division chief for unmanned aircraft, told FlightGlobal magazine in 2016.[73]

Defenders would either exhaust their stocks of missiles against cheap, numerous UAVs, or allow themselves to be overrun and destroyed. Swarms of Gremlins, Perdix and similar systems could potentially clear the way for manned aircraft to operate safely without opposition. Any military with this capability is likely to gain air supremacy and win a decisive advantage. Swarms may also be highly effective against battlefield targets at much lower cost than traditional precision-guided munitions.

Unlike cruise missiles, UAVs can carry out pre- and post-strike reconnaissance, and could potentially be used in larger numbers at lower cost. Attritable UAVs can be used with even less political consequence than existing armed UAVs as they are so easily replaced.

Another aspect of UAVs is that they are increasingly difficult to attribute. As events in Yemen and the Syrian Arab Republic show, operators may conceal the source of an attack, or it may be disputed. As explored in Paper Three in this series, this may pose challenges to managing conflict escalation within certain contexts.

Major powers currently run little risk of retaliatory strikes from military operations against distant minor powers, thanks to the distances involved, air superiority and missile defences. Small, long-range UAVs would in principle change this, allowing any State to carry out attacks anywhere. Any State could threaten or retaliate against any other State in the world.

Swarms present the possibility for mass-precision attacks where many targets are struck precisely, and without the collateral damage associated with traditional airpower. This capability may also

[73] J. Drew, "USAF's Small UAS Roadmap Calls for Swarming 'Kamikaze' Drones", FlightGlobal, 4 May 2016, https://www.flightglobal.com/news/articles/usafs-small-uas-roadmap-calls-for-swarming-kamikaz-424973/.

tempt States into 'show of force' attacks on power and communications infrastructure. Swarms could inflict, or threaten, mass civilian casualties more effectively than existing weapons.

Defence against small UAVs has become a high priority. The US military is budgeting approximately $1.5 billion for UAV defence in the next year. This is spread among a large number of projects, including missiles, guided projectiles, sensors, lasers, microwave weapons, jammers and electronic countermeasures. This diversity reflects the lack of any single, effective solution to the UAV problem.

Some commentators have suggested that UAV swarms will be easy prey for modernized mobile anti-aircraft systems.[74] These would be computer-controlled and radar guided and would fill the air with shrapnel fragments. However, such a defence would have to be 100 per cent effective; any UAV getting through might damage an anti-aircraft system, leading to its rapid collapse under the weight of the swarm. Moreover, such systems are expensive and so at best would provide defence for high-value installations and military formations only. Swarms might simply switch to softer targets such as logistics vehicles and foot patrols, or civilian targets.

The currently dominant military powers may have most to lose if the military balance is changed and they lose the ability to act freely. However, the greatest impact may be where one State acquires swarm capability which it believes could provide decisive advantage against a neighbour. This is especially destabilizing if it opens a window of opportunity to act before the neighbour acquires countermeasures—even if the technology is not as effective as anticipated.

These are the early days of a new and fast-moving technology. If no action is taken to develop standards, principles or regulation, States are likely to find themselves being carried in the slipstream of UAV technology rather than guiding it.

[74] S. Shmuel, "The Coming Swarm Might Be Dead on Arrival", War On The Rocks, 10 September 2018, https://warontherocks.com/2018/09/the-coming-swarm-might-be-dead-on-arrival/.

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Change in the air

Disruptive Developments in Armed UAV Technology

The Future of Armed UAVs Briefing Series supplements UNIDIR's 2017 study into Increasing Transparency, Oversight and Accountability of Armed Unmanned Aerial Vehicles (UAVs) to support States to consider whether there is a need to develop common understandings and principles for their transfer and use. Th first paper in this series identified trends which may raise new questions about the effectiveness of existing mechanisms and standards relevant to the transfer and use of armed UAVs. This paper identifies disruptive developments in armed UAV technology, and the third paper will consider what implications these developments may have for international security and stability in the future.

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