Air Mines

Countering the Drone Threat to Aircraft

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Moore's Law states that the processing power of electronic devices doubles every 18 months. This doubling has improved the capability of friendly military systems and those of our adversaries. Extrapolating this trend and other expected technological advancements suggests that by 2025 the currently widely proliferated "quadcopter" drones and their successors will have the capability to fly autonomously—at much higher altitudes, with longer flights—and be capable of complex formation maneuvers. These advances may happen soon since drones are already making strides in these areas. Additionally, drones will likely be produced with additive manufacturing printing machines at a low cost and may soon have weapons.[1]

Scenario: 12 October 2025, Kunsan Air Base, Republic of Korea

Tower: "Juvat 01, flight of two manned, two unmanned, line up and wait runway 3-6; Cyclops depredation in progress."

Juvat 01: "Juvats, line up and wait 3-6."

Tower: "Juvat 01, cleared takeoff runway 3-6; six Cyclops defeated."

Juvat 01: "Juvats cleared takeoff runway 3-6; check auto detect/fire, crush 'em!"

The Juvat flight of two manned F-16Vs and two drone wingmen "headhunters" (HH) take the runway for its close air support mission against the hostile Kim Jong Deux regime. Crew members arm their directed energy (DE) systems that will—with pilot consent—shoot swarm drones using their active electronically scanned array (AESA) with integrated infrared search and track (IRST) detect systems. Though the departing pilots and their drone wingmen have confidence in their onboard defensive systems, they are hopeful that the high-power electronic microwave (HPEM) beams fired by the tower have already dazzled or destroyed any threats. As the flight gets airborne, the pilots do not encounter additional "Cyclops" (drones) until they reach their area of responsibility (AOR). As the Juvat flight scans the AOR, the AESA/IRST sensors determine multiple small, near-stationary tracks swarming overhead friendly forces at 10,000 feet. With the help of data link systems providing fused additional surveillance data that include acoustic detection from other friendly remotely piloted aircraft (RPA), the pilots' systems triangulate and identify the threats and Juvat lead coordinates for an HPEM beam attack. The lead pilot considers a "hard kill" technique (shooting one of his air-to-air weapons that would yield a kinetic effect and destroy any hazardous material the drones may be carrying). However, intelligence assessed that the North Korean drones were not carrying weapons of mass destruction (WMD), and he elects to conserve his nonreplenishable missiles in accordance with his shot hierarchy. Unfortunately, as the attack commences, the unmanned HH02 wingman turns away from the formation, and the flight gets the text message "JL, HH02, MOTOR S2 FAIL, R2B, EMERG," indicating that there is an unknown problem in the drone's engine—possibly damage from foreign object debris ingestion from an enemy drone—and the drone immediately returns to base. HH02 is done for the day—if not a week or month.

This article assesses drones as a realistic airborne threat and reviews possible methods to counter this burgeoning technology. It begins by discussing the future drone threat and examines possible countermeasures to mitigate drone attacks against airborne assets, including DE and kinetic options. This research suggests that additional investment is needed today to counter the use of drone swarms that may be soon used as flak or as kamikazes against friendly aircraft.

The Threat

In 1921 Giulio Douhet argued in *The Command of the Air* that airplanes should be used as offensive weapons. He determined that if one desired to defeat his adversary, he should aggressively attack his opponent's air force in the air and—even more importantly—on the ground. Douhet was skeptical of air defenses like antiaircraft artillery (AAA) or "Triple-A," largely due to the low probability of hit (PH), which he compared to "a man trying to catch a homing pigeon by following him on a bicycle."[2] Much has changed since Douhet's writing, but the control of the air is still essential for effective friendly air and ground operations. What has changed, however, with regard to Douhet's theories, is the opportunity to attack enemy airplanes before they become a threat, a concept articulated by Winston Churchill in 1914: "the great defense against aerial menace is to attack the enemy's aircraft as near as possible to their point of departure."[3]

The idea of drones swarming and occluding the skies—waiting for aircraft to collide with them or even the concept of drones homing in on aircraft and scoring a kamikaze-like kill—seems analogous to the way hydrogen balloons were employed in World War II when belligerents used them as obstacles.[4] The idea may also be related to AAA capabilities and tactics proliferated against aircraft today.

In World War II, friend and foe alike used balloons that dangled thick, impenetrable wires to "area deny" low-level flying aircraft.[5] This tactic is known today in doctrinal terms as a "barrage defense;" it extends beyond balloons to AAA and drones that defend assets from airborne attack. Actors today fire artillery in specific areas hoping to hit approaching adversary aircraft, causing aircraft damage and preventing a successful strike. While these tactics in World War II were imprecise, with terms like *barrage defense* and *curtain fire*, modern technology allows more precision in targeting inbound aircraft. Today, radar-tracking systems allow for aimed-fire AAA, with an increased PH.

Analogous to aimed-fire AAA, drones will soon have a hunt-and-destroy capability. Algorithms exist today to program a drone with "see-and-avoid" ability as demonstrated at the Massachusetts Institute of Technology (MIT) with proven autonomous software logic. In the MIT study, a graduate student in the school's artificial intelligence lab used an open-source stereovision algorithm that enables a "drone to detect objects and build a full map of its surroundings in real time . . . at 120 frames per second."[6] One can infer that this algorithm can be reversed to see and *not* avoid.

These technological developments will enable drone employment with an offensive mind-set, not just as a defensive barrier as suggested in the MIT study. These drones are becoming more capable and cheaper. The table below shows a list of the top commercial drones available as of December 2016. Even as this article goes to press, the prices listed in the table are falling—some by more than 50 percent since 2015.[7]

Drones will also likely soon have significantly longer loiter time. Electric storage battery technology is advancing at a rapid rate. At the University of Cambridge, for example, "very high energy density, [and] more than 90 percent [efficient]" lithium-air batteries are showing promise to deliver a 10-fold increase in power and endurance, and these will likely be commercially attainable within the next decade.[8] This technology does not even account for other developments yet to be seen, like more efficient aerodynamics and lighter components. A 10-fold increase in battery power would yield a flight duration of more than three hours for several of the drones listed in the table.

While birds usually attempt a last-ditch maneuver to avoid approaching airplanes, such is not the case with a killer drone. Attack drones will have a high PH. By regulation, USAF pilots must terminate training missions if there is an actual or suspected bird strike; clearly, they would also need to terminate for a drone strike. For example, a recent RQ-7 impact with a C-130 in Afghanistan not only ruptured a fuel tank but also damaged a wing spar and the wing box.[9]

Collisions between aircraft and drones will be much more destructive than collisions with birds due to the material composition of the drone and the potential for higher relative airspeed of impact.[10] Alexander Radi, a researcher for the Australian Commercial Aircraft Safety Authority, notes that birds "behave like fluids" at impact, with "the disintegration and the flowing of the bird absorb[ing] energy, which decreases the impact forces."[11] Drones are different. A "non-deformable impactor . . . creates a localized strain field in the target material with high peak forces, which supports . . . material failure."[12] Such an impact, particularly near an engine, could result in engine failure that could be catastrophic—especially to single-engine aircraft such as the F-16 or F-35. Further, just as bird strikes force mission termination, an impact with a hard metal object would decrease mission success and increase aircraft downtime.

Table. December 2016 drone sampling

	Model Name	*Price (USD)*	*Flight Time*	*Other*	*Altitude (feet) / Speed (knots)*	*Size (mm) LxWxH*
Camera Drones	DJI Inspire 1[a]	$2,899	> 30 min.	obstacle avoidance	* / 40	~450 x 450 x 300
	DJI Phantom 4[b]	$1,399	18 min.	solid hover accuracy	19,685 MSL** / 38	350 mm diagonal
	Yuneec Typhoon H 4k[c]	$1,199	25 min.	transmission up to 1.6 km	* / 40	520 x 457 x 310
	3DR Solo[d]	$999	20 min.	15 min. battery with payload	* / 48	250 x 460 x 460
	Yuneec Q500 4K[e]	$929	25 min.	watch me and follow me flight modes	* / 15.5	420 x 420 x 210
	DJI Phantom 3[f]	$499	23 min.	16 feet per second climb rate	19,685 MSL / 31	350 mm diagonal
	Parrot Bebop[g]	$199	unknown	lightweight fiberglass (400 g)	unknown / 25	280 x 320 x 36
Racing Drones (carbon fiber) 250 mm-class FPV	TBS Vendetta[h]	$499	5 min.	3 km range	4265 AGL / unknown	230 x 220 x 50
	Lumenier QAV250[i]	$539	FPV (first person view) customizable airframe for 250 mm drones; specs depend on build options			
	IRC Vortex 250 Pro[j]	$499	Also depends on customization		unknown / > 60	250 mm class
	Eachine Racer 250 RTF[k]	$359	10–14 min.	30 m operating range	unknown	220 x 233 x 50
	IRC Vortex 285[l]	$329	Also FPV with OSD (on-screen display), having similar characteristics as other racing drones			
Toy Drones	Parrot AR Drone 2[m]	$250	12 min.		328 AGL / 22	517 x 517 x 127
	LaTrax Alias[n]	$97	15 min.		unknown / 15	166 x 166 x 43
	Blade Nano QX[o]	$74	8 min.	very little payload capacity	not specified	182 x 160 x 63.5
	Syma X5C[p]	$44	7 min.	30 m operating range	not specified	310 x 310 x 80
	Hubsan X4[q]	$34	13 min.	300 m operating range	not specified	76 x 25 x 10
	Proto X[r]	$30	unknown	weighs only .4 oz.	not specified	50 mm diagonal

(*Source*: Ranking, pricing, and type information are derived from http://myfirstdrone.com/tutorials/buying-guides/best-drones-for-sale/. Additional specification information is found on the websites referenced below.)

[a] http://www.dji.com/inspire-1/info#specs
[b] http://www.dji.com/inspire-1/info#specs
[c] https://www.yuneec.com/en_US/products/typhoon/h/specs.html
[d] https://3dr.com/solo-drone/specs/
[e] https://www.yuneec.com/en_US/products/typhoon/q500-4k/specs.html
[f] http://www.dji.com/phantom-3-pro/info
[g] https://www.parrot.com/us/drones/parrot-bebop-drone#technicals
[h] http://www.team-blacksheep.com/tbs-vendetta-manual.pdf
[i] http://www.lumenier.com/products/multirotors/qav250
[j] http://www.immersionrc.com/fpv-products/vortex-250-pro/
[k] http://drones.specout.com/l/396/Eachine-Racer-250#Specs
[l] http://www.immersionrc.com/fpv-products/vortex-racing-quad/
[m] http://drones.specout.com/l/93/Parrot-AR-Drone-2-0#Flight&s=2Av3Rl
[n] http://drones.specout.com/l/90/LaTrax-Alias-6608#Specs&s=1I04SX
[o] http://drones.specout.com/l/40/Blade-Nano-QX#Specs&s=1I04SX
[p] http://www.symatoys.com/goodshow/x5c-syma-x5c-explorers.html
[q] http://quadcopterhq.com/hubsan-x4-h107c-review/
[r] http://www.protoquad.com/protox.html

* Many drone specifications put 400' AGL (above ground level) as max height, which is the Federal Aviation Administration height restriction. However, drones are usually capable of reaching heights up to 20,000', provided the distance is within transmitter reception.

** Mean sea level

A common assumption in drone collision articles comparing damage from drone strikes to bird strikes is that drones will not be in flocks and thus have a lower PH than a flock of birds. This assumption is wrong if an adversary uses swarming tactics. While the technology is in its infancy, the Naval Postgraduate School (NPS) demonstrated swarming technology in August 2015, manually controlling 50 drones with a single controller.[13] The NPS used Wi-Fi and algorithms in its test, and it will soon add greater autonomy.[14] This capability is rapidly growing. Last year, the Intel Corporation built a holiday light show for Disney Springs near Orlando, Florida, with 300 drones in complex changing formations, also with a single controller.[15] Drones will also one day fly with payloads of bombs or WMDs, DE weapons such as lasers and high-power microwaves (HPM), and other miniaturized weapons. Yet even with just their nonorganic material and with a hunt-and-kill programming, swarming logic, and automation, drones will soon pose a substantial threat to aircraft and our combat readiness.

Countertactics

Enemy flak was a greater concern than barrage balloons in WWII, and many of the 22,951 US operational losses in WWII were attributed to it.[16] To improve the odds for survival, fighter and bomber pilots increased their altitudes and altered their courses.

With drones, countermeasures are not yet fully developed, but DE and kinetic kill devices have the potential to dazzle or destroy drones. While it is possible to "fire" DE ahead of a flight path to clear threats, collateral damage concerns make this option problematic. Minimizing collateral damage would require identifying a specific threat and selecting the right weapon to defeat it.

Detection options that can locate and identify drone threats include audio (hearing rotors), electronic emission, optical (visual tracking), radar, light detection and ranging (LIDAR), and infrared (IR). The challenge with all these sensing types is that they are only marginally effective in detecting stealth aircraft, such as the very large B-2 bomber with dimensions of 69 x 172 x 17 feet.[17] Detecting 40 x 40 millimeter drones will be much more difficult.

Current procedures for finding birds and other small hazards around airfields may help but will not solve the problems that already exist with the drone threat, as when a drone collided with a British Airways 727 on 17 April 2016. Tower controllers use binoculars to locate raptors and other smaller birds flying near arrival and departure corridors, and pilots make radio calls warning other pilots of bird threats. These procedures may be less effective with drones, considering their evasive ability and smaller-than-bird size. A swarm of 100 drones—that may in the future cost about $1,000 for the *entire* swarm—would be more visible than a single drone. However, an adversary's ability to decrease the swarm density by increasing the spacing between drones would decrease visual detectability. A belligerent may space drones in a pattern that optimizes PH based on the airframe size of the expected adversary aircraft, which may make visual detection difficult.

Quadcopters have a distinct high-pitch whine from their propeller blades and motors, and such acoustic signature presents one type of drone detection option. An acoustic detection system simply records the detected sound and compares it to known acoustic signatures in a database for identification using multiple sources for geolocation.[18] However, Zain Naboulsi, chief executive officer of Drone Labs, mentioned that while acoustic detection does add value to a multisource drone detection system—relatively easy to design, use, and purchase—it is not nearly as effective as other drone detection options, largely due to environmental noise and range limitations.[19]

Electro-optical (EO), commonly thought of as television systems, is used today as detect-and-track enablers in many weapons systems. Examples include advanced targeting pods flown on fighter aircraft to deliver bombs, like Northrop Grumman's LITENING "Gen 4" advanced targeting pod; air-to-surface missiles like in Raytheon's air-to-ground tactical missile AGM-65H/K Maverick; and in drone killer detection systems like Boeing's Compact Laser Weapons System (CLWS).[20] These weapons systems integrate charge-coupled devices (CCD) to produce high-resolution digital imagery. Many of the systems that use EO for detect also have an IR track capability that augments the EO sensor.

An IR mode could also help detect and track drones, although a drone's heat source is much smaller than a typical aircraft, requiring the system to have different operating parameters than those used in standard IRST systems. Still, IR detection should not be discounted for drone detection. For example, Figure 1 shows Boeing's CLWS using EO/IR to track a drone in a nonadverse weather setting.

One serious limitation of using EO/IR to detect and track drones is that adverse environmental conditions significantly degrade its capabilities. While technological advances like CCDs make electronic detection superior to the capability of the human eye, they are still affected by clouds, fog, and smoke. Drones and airplanes can still operate in clouds.

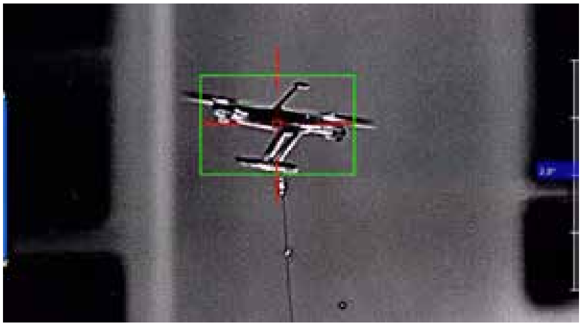

Photo courtesy of Boeing

Figure 1. EO/IR track on drone by Boeing's Compact Laser Weapons System

As a sensor, radar can detect drones, but legacy radars like the AN/APG-68 in most F-16s today would require upgrades in software coding and processing power. Even then, these older radars would have limited success in detecting the drones due to their small radar cross section and very small Doppler return, especially if the drone were nearly stationary and waiting for an approaching target.[21] Further-more, the APG-68 would have problems distinguishing a target from ground clutter or birds, meaning there would be many false returns that were not drones. If F-16s were upgraded with a radar like the proposed APG-83 scalable agile beam radar (SABR)—an AESA radar mentioned in the opening combat scenario—legacy fighters might at least have a chance at detecting the drones.[22] Radars like SABR would have much higher success since they would have greater resolution and frequency agility.

Another advancement that could aid in drone detection is LIDAR or laser radar. Essential technological breakthroughs are still needed for it to succeed in detecting airborne objects, but there is potential.[23] LIDAR can detect a jet's "exhaust trail [that] will contain concentrations of hydrocarbons on the order of parts per million, which can be 100 or more times the background atmospheric concentration."[24] The new Air Force Research Laboratory (AFRL) program named Vibration Interrogation for Battlefield Exploitation seeks to use laser vibrometer technology to detect engine vibration or other disruptions for identification.[25] Although drones may not have nearly as large an exhaust plume as a fixed-wing or larger RPA, LIDAR technology may still benefit drone detection. LIDAR still faces environmental constraints discussed above for EO/IR as its wavelengths have difficulty penetrating foggy or cloudy conditions. However, LIDAR can "see" through light haze—provided the obscurant is not so opaque that no photons return to the sensing source.[26] Many people today are becoming familiar with LIDAR, even if they don't know it, with self-driving cars and adaptive cruise control.

Any system communicating—whether from drone to drone with Wi-Fi, as was used in the NPS project, or with radio-frequency control like the many drone systems listed in the table above—emits signals that are detectable. A passive sensing-detecting system might also work to search for drone emissions, but the shortcoming of this detection tactic is that nonemitting drones will not be found. Locating such drones is very possible in the near future with autonomous drones that find their own targets without emitting or requiring any outside input.

Considering the systems discussed—their strengths and weaknesses—a system that integrates all of these resources for targeting would be greatly desired. On adverse weather days, radar and acoustic systems could still provide input, and on clear days all systems could work together to identify the targets, track them, and enable the kill via ground or airborne defense systems.[27] The engagement of a drone, once detected, still requires a kill mechanism. DE and kinetic drone defeat options are explored next.

The AFRL leads research for the Hybrid Defense of Restricted Airspace (HyDRA) study, looking specifically at DE defeat options (laser and HPM) that might augment kinetic alternatives for integrated air defense.[28] Depending on the lasing medium, lasers span wavelengths from the IR to the ultraviolet.[29] According to Dr. William Cooper at AFRL's DE Directorate, "A lot more has been developed with DE to high TRL [technology readiness level] than most people know."[30] This is good news because the USAF may need this technology soon. HyDRA is one of the ongoing AFRL DE programs that look specifically at DE options to augment kinetic defenses. The AFRL anticipates that these systems will provide near-term options to National Capitol Region defenses and then extend to meet the needs of combatant commanders. United States Pacific Command plans to use the technology on drones and potentially also against cruise missiles.[31] Dr. Cooper notes that even a low-kilowatt (kW) laser system "could likely easily neutralize" a drone at close range, adding that DE both minimizes collateral damage and ensures proportional lethality for Law of Armed Conflict legalities.[32] The AFRL has already demonstrated DE systems successfully against Group 1-2 Unmanned Aircraft Systems at Black Dart with MATRIX and MEGA HPEM systems (fig. 2).[33] Dr. Cooper, however, emphasizes that the "timeline [for development and fielding] really has a lot more to do with our corporate willingness to acquire, integrate and utilize the technology."[34] DE experimentation tests were conducted successfully in the summer of 2016 of 150 kW-class systems at the White Sands Missile Test Range (with detailed results classified). The AFRL also has an Advanced Technology Demonstration (ATD) project under way, known as the Self-Protect High Energy Laser Demonstration (SHiELD). The former is a General Atomics program using the High Energy Liquid Laser Area Defense System laser, and the latter is a $500 million ATD with AFRL and the Defense Advanced Research Projects Agency (DARPA).[35] According to Dr. Cooper, the future three-phase implementation plan for SHiELD will hopefully demonstrate its tactical usefulness and spur doctrinal change. However, he notes that not all phases are funded. Specifically, "Phase I implements a low-power pointing laser to demonstrate the ability to lock on and track targets. Phase II increases the power level. Phase III, if funded, would demonstrate a full-power system that could have podded residuals."[36]

Photos courtesy of Boeing

Photo courtesy of Orbital ATK

Figure 2. (*Left*) **Boeing Compact Laser Weapons System and** (*right*) **AUDS HPEM System**

Another system using laser defeat is Boeing's CLWS that needs only single-digit kW power to destroy its target in seconds.[37] Boeing touts its easy operation and portability, and technology experts equate the controller for the system that links the laptop to the controller of an X-Box 360 video game system.[38] According to Boeing, the CLWS will have relatively minimal cost and a range in the "tens of kilometers," requiring just a 220-volt outlet.[39] Boeing's program director stated the obvious benefit of not needing to replenish the armament: "The cost of the shot is basically the electricity to drive the laser. You're not firing a missile with all the cost of the logistical trail or cost of the missile or firing bullets where you have to worry about where they fall."[40] Stability and power requirements will continue as limiting factors in the near future of having an air-to-air laser kill, but the low kW demand potential, the future of battery advancements, and the minimal lasing time to affect a drone's destruction demonstrate definite potential.

Dazzle by definition is to "cause someone to be unable to see for a short time."[41] Laser beams can dazzle something (like a drone's optical sensor), but they are more likely to be used to destroy a target, like the design of the CLWS. An HPEM dazzle technique may destroy a drone, disable the drone temporarily, or "cook" key electronic components and render the drone ineffective.

The Anti-Unarmed Aircraft Vehicle Defense System (AUDS) was developed by three technology companies to dazzle drones and potentially take control of their navigation and control systems. Such a system could be very important if a hostile actor attaches WMDs or other ordnance to a drone, where free fall after engagement might generate casualties. The AUDS system purportedly can detect a drone at a range of five miles using EO/IR sensors, and then uses radio-frequency interference against the radio signals sent to the drone coming from the remote operator. When the drone picks up the AUDS signals, it "freezes, unsure of where to fly." What happens next is up to the new operator.[42]

As was the case for drone detection, multisystem queuing enhances DE attack capabilities, but even with it, there are still targeting limitations for both lasers and HPMs. The major weakness for laser technology is that foul weather can prevent or significantly degrade its success. On the other hand, while HPMs can engage through clouds, an enemy can counter HPMs with DE hardening. Conductive Composites Company, for example, recently layered nickel on carbon within a plastic-like material that can mold to other structures, like drone surfaces. This process mitigates HPM attacks by directing the energy around and away from the target—a concept similar to the idea of placing a Faraday cage around the drone.[43]

While DE is a choice weapon against drones due to its scalable and multiple-use capabilities, aircraft must still have kinetic kill options should they face a reduced visibility situation (lasers and IR) or an adversary having DE-hardened components. This article has focused mainly on fixed-wing aircraft that fly at fast airspeeds and higher altitudes—characteristics that add destruction to collisions—but many more aircraft are threatened by drones. Helicopters, for example, are also at risk to drones, considering that their operation is mostly in today's drone-prone, lower-altitude environment. Helicopter pilots today worry about other threats like man-portable air defenses (ManPAD) and rocket-propelled grenades (RPG), but increasingly pilots' combat sorties will also need airborne scan for drones. The RPG and ManPAD threats have the US Navy's (USN) attention, and the USN is quickly developing countermeasures that could also be useful for drone defeat.

The Helicopter Active RPG Protection (HARP, previously known as HAPS) is a product under development by the USN, with the objective of RPG detection and defeat. This concept can extend to killing threatening drones.[44] The HARP concept could also provide a kinetic kill option that could be developed for USAF aircraft.[45] A key interoperability of HARP is that the friendly-launched kill vehicle is designed to fire from an existing chaff and flare dispenser (integrated in the AN/ALE-47). Notably, the aircraft employing HARP would still have the ability to carry chaff and flare countermeasures, albeit in reduced amounts.[46] According to an Orbital ATK press release in February 2015, the HAPS vehicle "was able to launch, perform pitch maneuvers, and fly to a detonation point that simulated the location of an incoming rocket-propelled grenade" (fig. 3).[47] Optimizing the amount of blast and frag to kill an RPG or a drone is important. Jay Rodgers, the USN's HARP principal investor, states that "even blast alone is a tough kill mechanism for achieving effectiveness given kill vehicle warhead size constraints and how close to the aircraft the intercept is likely to occur." Thus, he continues, "enhanced blast and frag have better RPG [and drone] defeat potential. The enhanced blast is particularly attractive as it has greater effect than unaugmented blast but doesn't have the same lethal radius as fragmentation, a fratricide issue."[48]

Another USN program, Standoff Weapon Defeat (SOWD), which has similar RPG defeat concepts as the HARP program, touts being "useful as a drone countermeasure."[49] Users and investors in SOWD range from DARPA to the Secret Service, and over 10 Army agencies are involved in the program. However, only one USAF agency—the Air Force Security Forces Center—is involved in SOWD support.[50] This disparity is understandable based on the current base-defense-doctrine construct placing the majority of base kinetic defenses under an Army lead. But the USAF has to consider the utility of SOWD not only for air base defense but also for air-to-air engagements.[51] Further, as threats loom for flight departure and recovery corridors, the Air Force might have more of a doctrinal interest in those area defenses than does the Army, inviting application of more USAF resources.

Photo courtesy of Orbital ATK

Figure 3. Orbital ATK's HAPS kill vehicle

The USAF would also benefit from investing in a new kinetic weapon designed to kill drones—one that could cost less than the $1.55 million AIM-120D AMRAAM.[52] A cost reduction would be possible because the concept weapon would destroy smaller targets (less warhead required) and not travel as far (less propellant, etc.). The system could even be a friendly-launched drone that simply hunts enemy drones and kills them through impact or explosion. In summary, there needs to be multiple layers and options in the kill chain for destroying enemy attack drones. The sensors used for detection must fuse data from all sources mentioned above, and the war fighter should have both DE and kinetic options available for the kill.

Recommendations

Drones must first be detected before they can be killed, and doing so requires USAF investment in upgrades like an AESA radar for the F-16 and continued advancement of data fusion systems across all platforms. Air base security requires detection of drones before they fly overhead. While base defense is doctrinally an Army mission, the Air Force has a vested interest in protecting its aircraft. In the air, the USAF needs to invest in systems that enable detection of threats to aircraft thus allowing control of that particular air domain. The current drone threat suggests that we should pay close attention to aircraft departure and arrival corridors, in addition to clearing mission routes. In the end, these objectives necessitate having detect and shoot capability on USAF aircraft. For defeat, the USAF should not pick just one capability but should acquire multiple dazzle and/or destroy options, including DE and kinetic weapons. The DE research of the AFRL should be considered for air-to-air engagements, meaning that HyDRA needs funding and TRL advancement. Additionally, the USAF should develop a system similar to HARP for all aircraft that have countermeasure dispense systems. Finally, as drone proliferation threatens to overwhelm the combatant commander's base defense resources, all the services must work jointly to field and operate integrated, fused systems that protect war fighters.

Conclusion

In 1921 no individual, including Air Marshal Douhet, could have had the prescience to know the implications of Moore's Law or envisage the complexity of aerial systems in existence today. However, if Douhet were alive today, he could still repeat his time-tested words: "victory smiles upon those who anticipate the changes in the character of war, not upon those that adapt themselves after the changes occur."[53] He would also emphasize that winning air forces must immediately consider how drone warfare might change the character of war—a reflection that could reveal a need for prompt development of drone detect and defeat systems.

While some areas of technological advancement might slow, others are primed for a vertical launch trajectory. Even without the inevitable innovations in electronic components, swarm drone and/or singular kamikaze-like drone attacks on friendly aircraft are possible in the very near future. This eventuality demands a significant change to counterair doctrine and enlarges the concepts of detecting and defeating our adversaries. While there is no single panacea for defeating enemy drones, many options exist that provide increased success of operations in contested environments. Thinking of Douhet one final time, drone detect and defeat options should *absolutely not* be related to the improbability of a person catching a homing pigeon on a bicycle. ✪

Notes

1. This article uses the term *drone* to describe a class of small (Group 1) unmanned aerial systems that may be remotely piloted or, in the future—and more in line with the content of this paper—has autonomy (i.e., they could be not "remotely piloted" at all). This term is chosen also since it is widely used in the commercial industry, which sells drones like quadcopters, as referenced in this article. The Department of Defense (DOD) has a formal lexicon separate from the "drone" labeling in this article. For more information on what the DOD calls "unmanned aircraft systems," see UAS Task Force, Airspace Integration Integrated Product Team, *Unmanned Aircraft System* [*UAS, now remotely piloted aircraft, RPA*] *Airspace Integration Plan*, ver. 2.0 (Washington, DC: DOD, March 2011), http://www.acq.osd.mil/sts/docs/DoD_UAS_Airspace_Integ_Plan_v2_(signed).pdf.

2. Giulio Douhet, *The Command of the Air*, trans. Dino Ferrari (1942; new imprint, Washington, DC: Air Force History and Museums Program, 1998), 18, http://permanent.access.gpo.gov/airforcehistory/www.airforcehistory.hq.af.mil/Publications/fulltext/command_of_the_air.pdf.

3. Joint Publication 3-01, *Countering Air and Missile Threats*, 23 March 2012, IV-1, http://www.dtic.mil/doctrine/new_pubs/jp3_01.pdf.

4. Persons new to drone technology may not realize their current high proliferation or low-cost specifics; for detailed information and background on existing commercial drones, see the table in this article.

5. Maj Franklin J. Hillson, "Barrage Balloons for Low-Level Air Defense," *Airpower Journal* 3, no. 2 (Summer 1989): 41.

6. Mary Grady, "MIT Drone Avoids Obstacles Autonomously," *AV Web*, 4 November 2015, http://www.avweb.com/avwebflash/news/MIT-Drone-Avoids-Obstacles-Autonomously-225143-1.html," 1.

7. For example DJI's Phantom 3, which cost $1,299 in March 2016, had fallen to $799 by October based on pricing found on Amazon.com.

8. David Nield, "Researchers Create Lithium-Air Battery That Could Be 10x More Powerful than Lithium-Ion," *Science Alert*, 3 November 2015, http://www.sciencealert.com/researchers-have-created-the-ultimate-lithium-air-battery-with-super-storage-and-efficiency.

9. "C-130 Mishap Photos," *C-130.net*, http://www.c-130.net/g3/c-130-photos/Mishaps/Herkcollision, accessed 2 November 2016.

10. Such collisions do not even consider the possibility of a drone carrying impact-fused explosives.

11. Alexander Radi, *Potential Damage Assessment of a Mid-Air Collision with a Small UAV* (Monash University, Australia: Civil Aviation Safety Authority, 6 December 2013), 10.

12. Ibid., 3. Radi found that at collision velocities above 200 knots, the drone would likely "penetrate the fuselage skin, with potential of damaging internal systems" (ibid.). Most USAF aircraft will be flying well above this speed.

13. Rollin Bishop, "Record-Breaking Drone Swarm Sees 50 UAVs Controlled by a Single Person," *Popular Mechanics*, 16 September 2015, http://www.popularmechanics.com/flight/drones/news/a17371/record-breaking-drone-swarm/.

14. Ibid.

15. "Intel, Disney Light Up the Sky over Walt Disney World Resort with New 'Starbright Holidays' Drone Show," Intel news release, 16 November 2016, https://newsroom.intel.com/news-releases/intel-disney-starbright-holidays-drone-show/.

16. John Ellis, *World War II: A Statistical Survey: The Essential Facts and Figures for All the Combatants* (New York: Facts on File, 1993), 258–59. Mr. Ellis is clear that the 22,951 number is not perfectly accurate, and it is difficult to determine what a belligerent determined as a "loss." Researchers will find some variation in this figure. Ellis is able to conclude that flak was a major contributor to operational losses in WWII and thus uses the term "a large number."

17. USAF fact sheet, "B-2 Spirit," 16 December 2015, http://www.af.mil/AboutUs/FactSheets/Display/tabid/224/Article/104482/b-2-spirit.aspx.

18. Mark Pomerleau, "Drones: Findable, but Not Stoppable," *GCN*, 3 June 2015, https://gcn.com/articles/2015/06/03/drone-detection.aspx.

19. Zain Naboulsi (CEO, Drone Labs), teleconference with Lt Col Leslie F. Hauck III, 14 December 2015. Mr. Naboulsi emphasized that we are currently seeing an exponential increase in drone proliferation and capability, especially considering the new infusion of money from prominent technology companies like Intel to the Yuneec Company. He noted that "detection is hard" but possible and should not be left to just audible detection, which is easy but not optimal. For countermeasures, he stated that jamming is easy and is the "sledgehammer" against drones, as you can point and confuse them, and that "barrage noise is not elegant, but it is efficient." Naboulsi argued that electronic warfare is currently the most effective way to defeat drones but that in three to five years, encryption will make such technology much more challenging.

20. Andreas Parsch, "Designations of U.S. Military Electronic and Communications Equipment," 2000–2008, accessed 22 November 2015, http://www.designation-systems.net/usmilav/electronics.html.

21. From Colonel Hauck's experience.

22. Ibid.

23. Carlo Kopp, "Laser Remote Sensing—A New Tool for Warfare," Royal Australian Air Force Air Power Studies Center, 1995, http://www.ausairpower.net/ASPC-LIDAR-Mirror.html.

24. Ibid.

25. Graham Warwick, "Laser to ID Targets by Their Vibration," *Aviation Week and Space Technology*, 23 November 2015, http://aviationweek.com/technology/week-technology-nov-23-27-2015.

26. National Oceanic and Atmospheric Administration Costal Services Center, "Lidar 101: An Introduction to Lidar Technology, Data, and Applications," November 2012, https://coast.noaa.gov/digitalcoast/_/pdf/lidar101.pdf3.

27. Of course, adverse weather subjects the drone to similar difficulties in detecting its target, but the detection problem is made simpler by the relative size difference (the larger and noisier target is easier to detect) and at the same time more difficult (there is limited volume and power available in the drone to house more sophisticated detection equipment).

28. William Cooper, PhD, Directed Energy Directorate, Air Force Research Laboratory, Kirtland AFB, NM, to Hauck, e-mail, 4 November 2015; and Eileen Walling, *High Power Microwaves: Strategic and Operational Implications for Warfare*, USAF Center for Strategy and Technology, Occasional Paper No. 11 (Maxwell AFB, AL: Air War College, Air University, May 2000), 1.

29. Lexel Laser, "Laser Wavelength Charts," accessed 22 November 2015, http://www.lexellaser.com/techinfo_wavelengths.htm. These wavelengths can range from 238 nanometers (nm) (or even lower, depending on the phenomenology and beam coherence desires of a designer) with argon second-harmonic-generated and gas-ionized, beta-barium borate crystal lasers, to erbium-doped glass and solid-state lasers at 1,540 nm.

30. Cooper to Hauck, e-mail.

31. Ibid.

32. Ibid.

33. HPEM includes the entire spectrum, not just laser or HPM subsets.

34. Cooper to Hauck, e-mail. What this statement does not fully consider are the implications of the potential for collateral lasing damage beyond the target to friendly forces or the possibility that further range targets might not even have enough laser energy for destruction or dazzle at all; see the kinetic kill information in this article for other defeat options.

35. Ibid.

36. Ibid.

37. Jordan Golson, "Welcome to the World, Drone Killing Laser Cannon," *Wired*, 27 August 2015, https://www.wired.com/2015/08/welcome-world-drone-killing-laser-cannon/.

38. Ibid. In addition, kill time is a key factor; the laser that requires seconds to kill something will succeed over one that takes a long amount of time to achieve the same effect with low power. Adversary

maneuver increases the difficulty of targeting with laser technology, also problematic when there is not just a single drone (swarms). Collateral damage should also be considered with higher-power lasers.

39. Queena Jones, "This Drone Is Toast," *Boeing Frontiers Magazine* 14, no. 6 (October 2015), http://www.boeing.com/news/frontiers/archive/ 2015/october/index.html#/1/17.

40. Ibid.

41. *Merriam-Webster*, s.v. "dazzle," accessed 22 November 2015, http://www.merriam-webster.com/dictionary/dazzle.

42. Elizabeth Palermo, "Signal-Scrambling Tech 'Freezes' Drones in Midair," *Live Science*, 10 October 2015, http://www.livescience.com/52448-new-tech-freezes-drones.html.

43. Patrick Tucker, "A New Material Promises NSA-Proof Wallpaper," *Defense One*, 23 October 2015, http://www.defenseone.com/technology/2015/10/new-material-promises-nsa-proof-wallpaper/123066/.

44. Office of Naval Research (ONR), "Helicopter Active RPG Protection (HARP)," ONR BAA Announcement N00014-15-R-BA14, USN Science and Technology, accessed 12 January 2017, https://www.onr.navy.mil/~/media/Files/Funding-Announcements/BAA/2015/N00014-15-R-BA14.ashx

45. The USN moved from the Helicopter Active Protection System (HAPS) to HARP in 2014. HAPS brought the kill vehicle technology to TRL-3, and HARP is planned to take the system to TRL-6 with "live fire RPG arena defeat and inert RPG intercept demonstration from a helicopter in a tethered hover in 2019," according to Mr. Joseph Rodgers, Associate Fellow, Naval Air Systems Command, Combat Survivability Division, Assault Support, HARP Principle Investor, Washington, DC, e-mail to Hauck, 5 February 2016.

46. Rodgers to Hauck, e-mail, 22 November 2015.

47. Business Wire, "Orbital ATK Completes Key Test of Helicopter Active Protection System," 24 February 2015, http://www.businesswire.com/news/home/20150224005136/en/Orbital-ATK-Completes-Key-Test-Helicopter-Active.

48. Rodgers to Hauck, e-mail, 23 November 2015.

49. Jeffery Jones and Mark Bradshaw, briefing, subject: Joint Integrated Product Team for Standoff Weapon Defeat Overview, Physical Security Enterprise and Analysis Group, US Navy, Washington, DC, 28 April 2015, 3.

50. Ibid., 5.

51. John Geis, Grant Hammond, Harry Foster, and Theodore Hailes, *Deterrence in the Age of Surprise*, Occasional Paper no. 70 (Maxwell AFB, AL: Air University Press, January 2014), 43–44.

52. Office of the Under Secretary of Defense (Comptroller), *United States Department of Defense Fiscal Year 2016 Budget Request: Program Acquisition Cost by Weapon System* (Washington, DC: DOD, February 2015), 5-2, http://comptroller.defense.gov/Portals/45/documents/defbudget/fy2016/fy2016_Weapons.pdf.

53. Douhet, *Command of the Air*, 30.

Lt Col Leslie F. Hauck III, USAF

Colonel Hauck (MA, Air University and Naval War College; MS, Embry Riddle Aeronautical University) is the chief of special technical operations at Headquarters, US Air Force. He authored his professional studies paper on drones while attending Air War College at Maxwell AFB, Alabama. Before attending Air University, he served as an F-16 deputy group commander at Luke AFB, Arizona. Colonel Hauck received his commission from the US Air Force Academy, Colorado Springs, Colorado, and is a career F-16 pilot who has served in multiple positions including 80th Fighter Squadron commander and 310th Fighter Squadron director of operations. He most recently deployed as the deputy commander, 455th Expeditionary Operations Group (EOG), Bagram Airfield, Afghanistan, where he led combat operations and had senior airfield authority delegated duties at the EOG-level for eight squadrons, including A-10, MC-12, F-16, HH-60, EC-130, C-130, and aeromedical evacuation squadrons. Colonel Hauck is a command pilot with more than 2,100 hours, including 285 combat hours in support of Operation Enduring Freedom.

Dr. John P. Geis II, Colonel, USAF, Retired

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