Nightfall

Machine Autonomy in Air-to-Air Combat

Capt Michael W. Byrnes, USAF*

Although one finds no shortage of professional and academic conversation about remotely piloted aircraft (RPA) and potential unmanned combat aerial vehicles (UCAV), there is a distinct lack of forecasting of their futures on the basis of a tight fusion of tactics, technology, and the enduring truths of air combat. This article claims that a tactically autonomous, machine-piloted aircraft whose

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design capitalizes on John Boyd's observe, orient, decide, act (OODA) loop and energy-maneuverability constructs will bring new and unmatched lethality to air-to-air combat. It submits that the machine's combined advantages applied to the nature of the tasks would make the idea of human-inhabited platforms that challenge it resemble the mismatch depicted in *The Charge of the Light Brigade*. A convergence of new technologies indicates the earliest stages of emergence of a tactically game-changing approach to air warfare, but the institutional Air Force appears skeptical—perhaps since this theory of air dominance begins life in an environment resistant and rightfully cautious toward its development.[1] To date, a credible RPA optimized for air combat has not been developed, and the nation and service face severe fiscal austerity, increasing risk aversion.[2] Furthermore, the idea of a machine outflying the world's best fighter pilots may frustrate and unsettle conventional wisdom, inviting political contention.

However, if logic proves the dominance of this theory of machine autonomy in airpower and if the technology to execute it emerges, then making the emotional decision to reject it places our forces at strategic risk. To show that such claims are reasonable, the article presents a notional UCAV termed *FQ-X* to provide a guided tour through emerging real-world technologies and to show their tactical implications in an engagement. The discussion shifts to assessing briefly how these tactical effects ripple into the operational and strategic and then closely examines autonomous decision making in the context of the OODA loop before taking a deep dive into the technologies behind machine pilotage. Finally, the article counters prominent objections to the machine pilot in the arenas of cyber defensibility and the ethics of killing by a proxy weapon capable of making its own decisions. It wraps up with an assessment of the tactical and cultural integration challenges that lie ahead for the Air Force at the appearance of these novel systems.

FQ-X Design and Features

The form of a machine like FQ-X, whose purpose is to find and destroy enemy aircraft, will favor small size and weight, great speed, low detectability, and unprecedented accuracy. The design exploits cutting-edge metamaterials that complement radar-absorptive materials to generate specific tactical advantages. Metamaterials are synthetic structures that demonstrate effects previously thought physically impossible. Specifically, negative-index-of-refraction metamaterials are capable of refracting electromagnetic energy in a way that “bends” it around (rather than bounces it off) an object, rendering it invisible in a particular region of the spectrum. Researchers proved techniques to do so as early as 2001 and less than 10 years later in the visual and infrared spectra.[3] By 2012 a team had even devised methods to overcome geometry and polarization limits, which were showstoppers for the use of metamaterials to hide a large object like an aircraft.[4] The implication for airpower is that a new generation of extremely stealthy materials is emerging, and the military does not have the luxury of keeping them a secret. Their utility in a variety of civil and military applications may also lead to their relatively cheap and plentiful manufacture. Although no stealth technique is flawless, metamaterial layers within a dielectric composite skin of FQ-X severely hamper current detection and identification methods. Preventing an enemy missile lock on an FQ-X is an excellent return on investment, but the overriding reason for stealth is that FQ-X focuses religiously on the OODA loop. The priorities are to defeat the operator’s decision cycle first and missile-guidance systems second. When the aircraft is successful at both, it sidesteps a staple of modern air combat, undermining a multibillion-dollar national security investment.[5] When a scenario does not permit slipping past the allowable weapons-employment zone of air-to-air missiles, existing countermeasures and emerging directed-energy point defenses are excellent options for an aircraft with millisecond reaction times.[6]

Defensive capabilities are of limited value if not paired with tools to find, fix, identify, and target hostile aircraft. Radar technology has evolved to the point that superficial assumptions about its capabilities are no longer accurate. For example, it would be natural to think that if a transmitting aircraft sends out a pulse of energy to detect an opponent, then that opponent (who was just hit with that energy) should be able to notice and respond. However, modern radars with low-probability-of-intercept technologies transmit at power levels below the receiving aircraft's detection threshold, working across multiple frequencies and across time to integrate the collection of weaker returns into a coherent signal.[7] Modulation techniques applied to active electronically-scanned-array antennas allow for multiple beams, which translates to multiple target acquisition and engagement.[8] The key to all of these fantastic capabilities is the capacity for digital signal processing.[9] The principle of "first look, first kill" belongs to the aircraft with the most processing power and the best software to leverage it. F-22 processing power is on the order of 5 billion decimal operations per second.[10] Modern graphics processing units can execute digital signal processing for radar applications at 10 to 100 times that speed and are available as affordable commercial off-the-shelf hardware.[11] FQ-X uses arrays of graphics processing units to showcase how much the "find and fix" stage of air combat is really a battle for computing power, which it leverages from general-purpose hardware, shifting task specialization into software to reduce cost and increase flexibility.

Today's predominant use of guided missiles is already an implicit admission of reliance on automation, and if the machine pilot can outperform human processing in the most allegedly artistic piece of air combat, simpler ones also likely favor the machine. To demonstrate, FQ-X collapses to gun range to outmaneuver the modern human-inhabited fighter, exploiting both positive and negative G choices. FQ-X's options are flexible, thanks to carbon nanotube composite structures and the absence of a human inside. Carbon nanotubes are microscopic structures formed in 1952 lab experiments that did not reach broad awareness in the Western scientific community until 1991.[12] In 2012 researchers at North Carolina State University demonstrated fabrication of large-scale carbon nanotube materials that showed a remarkable 30 percent improvement in specific strength over the world's best-engineered composites.[13]

Once positioned to attack, FQ-X needs to deliver hyperprecise effects to maximize use of a comparatively lean arsenal that a small craft is likely to contain. To that end, it has a nearly all-aspect targeting system accurate enough to pick a particular spot on an opposing aircraft to place a high-explosive round or directed-energy burst. To positively identify the target and hit the desired spot, FQ-X must have integrated multispectral optics and computer vision software. One of the largest commercial drivers of this object detection software is Google (which pursues the technology for image-based search engines).[14] However, open-source projects like OpenCV, containing more than 2,500 optimized detection and recognition algorithms, are also rapidly advancing application of the science.[15] Computer vision frameworks such as OpenCV also take advantage of graphics processing units to speed processing functions five to 100 times faster than traditional computer hardware.[16] Figure 1 depicts an engagement approaching this end-game state from FQ-X's computer vision perspective, first from a notional US system's display and then from a hypothetical competing foreign version.

Figure 1. Dealer's choice: Mock-up graphics of computer vision for a sixth-generation approach. (USAF stock image of F-35A in flight and author's rendered image of J-20 using royalty-free 3D model purchased at TurboSquid, http://www.turbosquid.com/FullPreview/Index.cfm/ID/745460. The author edited both images to illustrate basic object detection, recognition, and tracking principles inherent in the field of computer vision.)

With clearance to engage, it fires an armor-piercing high-explosive incendiary round into a critical system like the first compressor stage of an engine, rapidly ending the engagement with little opportunity for the adversary to adapt. FQ-X, on the other hand, learns from every detail of the encounter with real-time machine learning. It can pass lessons to other UCAVs, making partnered aircraft smarter by every engagement. Besides direct aircraft-to-aircraft sharing, the FQ-X air vehicle can send its telemetry to a ground control station (GCS). In the event an air vehicle is destroyed, its last moments may be stored on a secure network via the GCS. The implication may not seem obvious at first, but contrasted to the loss of a human-inhabited fighter, the difference is staggering. Losing a human pilot is a tragedy, and in cold but factual terms that a commander must face, it means the loss of an enormous investment of time and money in training and operational experience. If a veteran pilot falls in combat, then a young rookie has to take his or her place, starting a cycle of development all over again. The machine pilot, however, learns from death and in near real time commits adaptations to other UCAVs in the fight. Opponents may find that the same tactic never works twice against these systems.

Implications: Ripping into the Operational and Strategic

If machine-controlled maneuvering and accuracy make every cannon round a "golden BB," then left unchecked a single FQ-X with a few hundred rounds of ammunition and sufficient fuel reserves is enough to wipe out an entire fleet.[17] The economics of this approach are similarly stunning to consider and require examination with a global airpower perspective. The Russian-Indian jointly developed FGFA (PAK-FA derivative) is still several years from reaching initial operational capability and seems subject to the same delays and cost spirals of any highly complex development program.[18] Conservatively, current estimates are about $100 million per copy and likely to rise.[19] On the US side of the equation, each Raptor has a flyaway cost of $148 million, each F-35 in low-rate initial production was $153 million during 2011, and a fighter pilot costs an estimated $2.6 million.[20] An AIM-9X missile is approximately $300,000.[21] If the aircraft and crew are fixed setup costs and their weapons are marginal costs of engaging a target, then the FQ-X system is poised to become substantially more affordable than the fifth-generation fighters it is engineered to overcome. FQ-X has a high percentage of commercial off-the-shelf hardware, small size, and no need for a one-to-one crew-to-aircraft ratio. The marginal cost for two stabilized cannon rounds fired at close range is a mere $20.[22] A rechargeable directed-energy weapon's cost to employ would depend on maintenance required per 100 firing cycles but would be inexpensive in a mature design.

Any compromise of defensive counterair ability jeopardizes high-value airborne assets, tanker and mobility aircraft, and the Airmen aboard them, opening the possibility for losses on a scale that our own service has not endured since its bombers attempted daylight raids in the 1940s.[23] The difference between then and now, of course, is that our industrial production base and budget are not configured to replenish such high attrition. In our efforts to become an effects-based force, we redefined mass by concentrating more capabilities in fewer physical assets, and that strategic choice has trade-offs.[24] Europe, Russia, India, and China have followed us into the game of big, high-tech fighter projects as well, thus framing a global problem-solving mind-set about how nations build airpower.[25] With so much depending on the current paradigm, an aggressor FQ-X performing as advertised in a US Air Force Weapons School event would become an inflection point in airpower history. Assuming that sixth-generation systems will simply be refinements of their fifth-generation predecessors falls well short of positively revolutionizing lethality, economy, and capability of airpower, and it invites increased risk to our current assets.[26] The path forward to continued assurance of air dominance starts by redefining our most basic understanding of what an airplane is and continues by applying well-established truths about air combat to new technological opportunities.

Flying Machines: Heart of the OODA Loop

Aviators instinctively see the airplane as a machine whose purpose is to fly rather than a machine that flies to serve its purpose.[27] However, if the Boyd cycle lies at the heart of describing success in air combat, then it makes sense to give priority to the elements of an aircraft most responsible for supporting speed and accuracy in the OODA loop and call all others secondary. RPAs and UCAVs are computers with airframes strapped to them, not the other way around. Flight-control actuators, avionics, radios, sensors, and even weapons are like plug-and-play peripherals for this platform, just as one might plug in printers, scanners, or cameras to a personal computer. This view reveals an opportunity to affect the flexibility and affordability of sixth-generation airpower. Decades ago, open architecture of IBM PC clones enabled massive proliferation of computing technology.[28] Similarly, pursuing plug-and-play standards, commercial off-the-shelf hardware, and common operating systems for autonomous aircraft and their GCSs supports proliferation and cost reduction that help to accelerate the pace of research, development, testing, and operational use. A tactically autonomous aircraft like FQ-X need not seek science-fiction-like self-awareness; within the scope of air-to-air combat, it is an airborne computer that executes the underlying mathematical truths of what human combat pilots do in the cockpit, doing so more quickly and with more precision.

Boyd's OODA loop implicitly reveals that the "art of flying" is actually a cyclical processing activity. It includes sensory data acquisition, reconciliation against known information to derive meaning, selection of a response from a known repository of possible choices or synthesis of a new option when none is satisfactory, and execution of the choice. Machine-learning algorithms address these tasks in two modes: supervised (designers train the software by telling it right from wrong) and unsupervised (it determines if a new action is right or wrong by experimentation and by extension of what it already knows).[29] A machine pilot with appropriate sensors and multiple computing cores can acquire and integrate information from diverse sources more quickly and reliably than a human.[30] With a trained artificial intelligence (AI), it can also draw clearer interpretation from data without human psychological biases. Humans average 200–300 milliseconds to react to simple stimuli, but machines can select or synthesize and execute maneuvers, making millions of corrections in that same quarter of a second.[31] Every step in OODA that we can do, they will do better. Although Boyd's hypothesis is a cornerstone of fighter aviation, an inadvertent consequence of its logic in this evolving context is that machines will inevitably outfly human pilots. Furthermore, machine pilots do not have continuation-training requirements or currencies to maintain.[32] Unlike humans, whose skills regress without reinforcement, tactically autonomous aircraft can "sit on a shelf" for extended periods of time and remain exactly as sharp as they were the day they were pulled from service. Budget sequestration grounded 17 squadrons and did long-term damage to combat readiness—an effect that autonomous airpower would not suffer from. That $591 million cut represents an overhead cost which simply would never have existed in the first place with machine pilots.[33]

Tactical Autonomy Today

A common objection to this application of the OODA loop claims that the machine will not be able to do one or more of these tasks at the same level as human cognition, particularly the "orient" and "decide" steps. One author concludes that "the information required to make such a decision [to fire weapons] comes from so many sources and could be so easily spoofed or jammed by the enemy, that the validity of that computerized decision could never be fully trusted."[34] Unfortunately, he presents no discussion of the specific technical challenges and solutions, instead generalizing to conclude that "what separates men from machines is the ability to see opportunity and use it creatively."[35] In fairness, that author's point was not "anti-unmanned aerial vehicle (UAV)" but a wise call for caution about how much faith we put in these yet immature aircraft. Still, reconciling his perspective against recent technical developments reveals that his viewpoint does not anticipate the direction in which machine pilotage is evolving.

In 2012 the Defense Science Board released a study on the role of autonomy in Department of Defense systems, finding significant opportunity for RPAs to further leverage existing computer vision, AI, and machine-learning technologies to add value through onboard autonomy.[36] To get a sense of how underexploited existing AI really is, consider that in 2008 an MIT researcher (and former F-15C pilot) successfully executed machine-learned, real-time, basic fighter maneuvering using a neurodynamic programming technique in a flight-test lab.[37] The software adapted rapidly and learned to maneuver into a weapons-employment zone by discovery rather than by being taught exemplar tactics (fig. 2). The MIT work shows that the basis for autonomous unmanned fighters exists in building blocks and that future maturation would add sophistication to take the technology beyond the lab and into complex flight environments.[38] In another compelling development that would facilitate machine pilotage, researchers in the AI subdiscipline of neuroinformatics recently constructed "neuromorphic" chips that behave like synthetic neurons on silicon substrate, imitating brain function and allowing incorporation of complex cognitive abilities in electronic systems.[39] A University of Zurich team presented a design capable of performing complex sensorimotor tasks that, in an organic brain, require short-term memory and context-dependent decision making.[40]

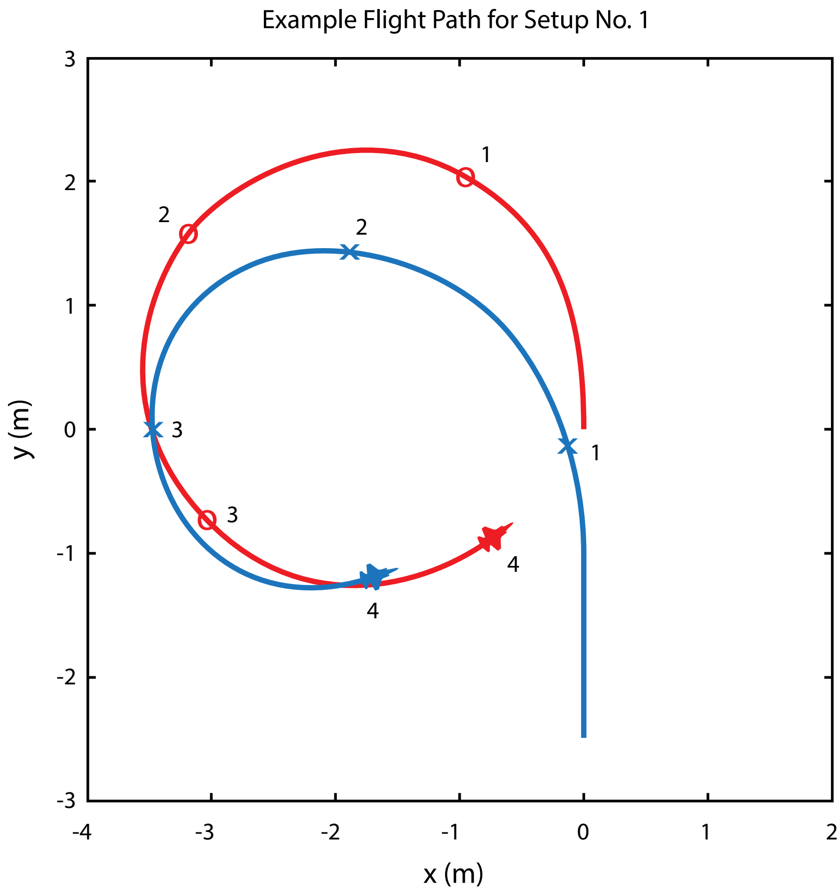

Figure 2. UAVs learning basic fighter maneuvering from a perch setup. (Adapted from James S. McGrew et al., "Air-Combat Strategy Using Approximate Dynamic Programming," *Journal of Guidance, Control, and Dynamics* 33, no. 5 [September–October 2010]: 649. Reprinted with permission from James S. McGrew.)

An applied information technology perspective and increasingly evolved AI technologies suggest that new UAVs will thrive when granted tactical autonomy. These machines cause us to revisit the notion of "centralized control, decentralized execution." This codified Air Corps doctrine, born in a world without real-time video feeds, taught that commanders of an air campaign had to grant crews a high degree of autonomy, entrusting them to accomplish a mission.[41] Later, real-time connectivity to the cockpit (or a GCS in control of a remote aircraft) allowed commanders to be as tactically hands-on or -off as they saw fit.[42] With FQ-X, autonomy for the conduct of the engagement would return to the air vehicle to take advantage of its superior processing speed and reaction times. The Defense Science Board study, however, points out that a machine's autonomy to perform tasks does not preclude its adherence to rules of engagement or suggest that it is totally absent of human supervision.[43] Human decision making at a higher level is crucial to bridge the tactical to the operational, but these machine-pilotage technologies suggest that stick-and-rudder skills might not be an Airman's central value proposition.

Hacking the Mission

Reliability of the machine pilot is a natural concern. Potential defects in the design are more likely than computer hacking and are most effectively abated through comprehensive testing demanded by the best practices of software engineering. The fear of cyber attack relies on the belief that any computer system can be hacked.[44] A more accurate answer, however, is that breaching the security of an information technology system *requires the defender of that system to make a mistake in design or operation*. In highly complex systems, that fact leads to a cycle of vulnerability discovery, analysis, and repair or mitigation. It is therefore critically important to engage in thorough testing and security reviews at every step of the system's design and to keep the authorized user's opportunities to commit an unsafe act to a minimum through excellent design of human-computer interaction.[45] All "cyber" attacks are attempts to negatively affect the confidentiality, integrity, or availability of a system.[46] Like their counterparts in the kinetic realm, they are observable, repeatable tactical actions that one can study and counteract.

The intersection of classically kinetic air combat and more novel cyber activities paints a fascinating picture of the potential employment methodologies and skill sets demanded of crews that operate assets like FQ-X. From a cyber-defense perspective, for example, shooting down the air vehicle falls under the category of a physically based attack against system availability.[47] A fighter pilot would simply say, "You lost and got shot down," analyze the tactical reasons in a debriefing, and teach how to win next time. Both perspectives are simultaneously valid, and both mind-sets extend from common points of overlap in different directions: one toward a very kinetic, visceral, tactical set of problem-solving skills, and the other toward analytically preventing exploitation of a computer system. A design like FQ-X is subject to the rules of both worlds and needs those employing it to operate in a unified framework that addresses both air combat and cyber-defense concerns. The cyber defender is unlikely to be able to look at an air battle and integrate tactical- and operational-level concerns to prosecute a war. The fighter pilot is unlikely to be able to detect and counter an enemy's attempt to launch a complex exploit against the UCAV's operational flight program. The good news for the US Air Force is that it has a rich heritage of expertise at all levels of air warfare and is actively developing capability in the cyber realm.[48]

Ethics of Autonomy

As frequently as skeptics cite hacking as a potential weakness of unmanned flight, consideration of the ethics of autonomous weapons employment captures far more public apprehension. The discussion sits amidst a much larger and more ambiguous debate about remote and robotically enabled warfare. A search on Amazon for "drone warfare" books revealed nearly 30 promising titles and almost 200 total results. A Google Scholar search for the same topic returned 14,800 results. A third of the *Routledge Handbook of Ethics and War* is dedicated to drone and cyber topics, and the entire cover image depicts an armed MQ-1B.[49] *Jus in bello* (the justice of conduct in war) arguments regarding the use of RPAs focus much of their contention on targeting criteria, collateral damage, and debates about the wisdom of overreliance on military instruments of power. Those issues are important national discussions, but to cut through the noise of so many conversations and emphasize the ethics of truly tactically autonomous combat calls for a scholarly work like Armin Krishnan's *Killer Robots*.[50]

Krishnan clearly delineates between the types of robotic systems involved in the military's trade, and the FQ-X concept intersects his definitions of the terms *unmanned aerial vehicle* and *autonomous weapon*.[51] He raises the concern that once an advanced machine demonstrates capability and offers the economy of not having to pay health care or retirement benefits, the military and its political masters will become fixated on the efficiency and convenience of replacing humans on the battlefield. If they do so, perhaps also seeking the political convenience of minimizing casualties, they will fail to consider the qualitative, long-term consequences of that choice.[52] The irony of a pure, unbridled quest for combat efficiency, as political-military strategist Thomas K. Adams points out, is that sooner or later the inventors realize that humans are always the weakest link in a system. They optimize human operators and then human decision makers out of the equation to replace them with another machine. As an argument to the extreme, he suggests that the cycle repeats until the tactical level of war involves no humans at all, rendering the whole activity a pointless waste of resources that fails to resolve the human needs that triggered it in the first place.[53] A government must respect the ethics of its civilization and consider what statecraft and warfare communicate to the world about its people. In the case of FQ-X, the most pressing question concerns whom to hold responsible for the conduct of a proxy weapon that makes its own decisions.

If the device functions as intended, the ethics are simple: the UCAV is an extension of the will of the person who commanded it, and the chain of responsibility traces from the operator up the kill chain of the command and control structure. If, however, the system deviates and kills people the operator never intended to harm, then assignment of blame becomes more complicated, calling into question the degree of autonomy one can grant a machine and how much human supervision must remain in the kill chain.[54] The Air Force encountered a parallel situation in which a complex system broke down during the 1994 Blackhawk incident. Skilled Airmen working across multiple platforms to control airspace utterly failed, and 26 people died unnecessarily as a result. That system was defined by people, policies, practices, training, technologies, and rules of engagement. In the end, not one person went to jail because of the incident.[55] Systems like FQ-X will similarly employ procedural guidance to reflect a combatant commander's intent, though translated into a digital form subject to error checking and closer scrutiny. Regardless of analog or digital means, however, an enduring takeaway of the Blackhawk incident appears to be that attaining the satisfaction of justice becomes difficult when responsibility is diffused in complex systems. We must deliberately plan how to take responsibility for the things we intend to create; otherwise, we will have no more satisfying answers than we did in 1994—or in any friendly-fire or civilian-casualty event before or since.

Ethical debates guide the implementation of any new means of war fighting, making a technology either admired or monstrous before the court of public opinion. Autonomous weapons must reconcile a tactical desire to exploit the benefits of their independence—for example, reducing signatures by disabling data links during an engagement—with our moral need to limit the diffusion of responsibility to nonhuman actors in a system. One solution is to break the autonomous air-to-air engagement into five phases—searching, stalking, closure, capture, and kill—and then assign discrete levels of autonomy and operator interaction per phase.[56] This approach would allow the UCAV to maximize its time under autonomous, low-detectability conditions and reach back to its human operator at key junctures where moral questions trump the tactical risk. Another method would authorize firing freely on enemy unmanned systems but require operator consent to take a human life. Such techniques are merely extensions of existing methods of managing lethal autonomy.[57] Joint terminal attack controllers call for close air support in one of three types, and each type allows the pilot (a semiautonomous entity to the controller on the ground) different degrees of freedom.[58] Just as air forces build the ground component's trust in airpower, so must UCAV designers progressively prove new systems—as one author suggested might be appropriate in pursuit of an optionally manned design for the Air Force's next long-range bomber.[59] This line of thinking is consistent with the Defense Science Board's study on the role of machine autonomy.[60]

Integration and Cultural Issues

Air forces that have an ecosystem of aircraft specialized in distinct tasks succeed over those with aircraft designs burdened by divergent workloads. L'Armée de l'Air learned that lesson disastrously at the hands of the Luftwaffe in 1940.[61] Systems with the capacity for tactical autonomy, like FQ-X, will not go to war alone and will need to integrate their capabilities with dissimilar UAVs and human-inhabited vehicles. Autonomous aerial refueling, for example, may manifest from follow-on work after the Defense Advanced Research Projects Agency's KQ-X project or the Navy's unmanned combat air system demonstrator.[62] If so, KC-46 acquisition just beginning in the midst of UAV advances suggests a long period of overlap with both manned and unmanned platforms providing global reach. The exact pattern of integration—which assets will be autonomous, remotely piloted, or human inhabited—will have as much to do with availability of assets that can do the job as with the combatant commander's vision, preferences, and comfort level. Certainly, a strong need will exist for deep, pervasive integration across all available air assets in order to maximize the utility of every platform in the ecosystem of an air force.

Recent discussion of how to fit future autonomous and remotely piloted systems into an air order of battle and into the cultural fabric of the service has been lively in *Air and Space Power Journal*. The prevailing theme is that semiautonomous UCAVs will serve as wingmen while the manned fighter remains the centerpiece of air warfare. The most disturbing thing about this notion is that it attempts to serve two masters: avoiding saying anything upsetting while also trying to advance the development of UAVs. It is also strictly "forward pass" thinking, as if chair-flying an ideal sortie without simulating enemy responses in a "backward pass" through the concept.[63] Its assumptions are that (1) force multiplication is all we require of UAVs and (2) in air combat, none of these platforms can defeat manned fighters directly. One author even states that they "will not replace the manned fighter aircraft—we cannot build a control system to replicate the sensing and processing ability of trained aircrews."[64] That article offers neither technical nor research data to qualify its indefinite, unrestricted claim. In light of the research evidence in favor of machine pilotage, that statement is suspect.

In another article from the same release of the *Journal*, Maj David Blair and Capt Nick Helms suggest that manned-remote fusion represents the future of airpower and argue that the principal hindrance to realization of that future lies within Air Force culture rather than technology.[65] Their analysis seeks to reconcile the roles of these two breeds of airpower and their accommodation within the Air Force's operational culture. However, it also envisions the fusion of manned assets and UAVs whereby human-inhabited assets unquestioningly lead the fight into contested airspace. It never stops to ask whether the application of Boyd's words to this emerging technology would actually render such a future improbable. As a competing construct, FQ-X pushes OODA to nanosecond resolution and argues that the air-to-air decision-making cycle of a human pilot, at its best, could never logically win a direct contest with pure machine autonomy—meaning that competition for primacy does in fact exist.

Still, they believe that

> the true conversation does not deal with competition between humans and machines. Instead, it concerns the nature of cooperation between them. . . .
>
> . . . The fear that pilots are replaceable is best answered by using the lens of technology to amplify the things truly irreplaceable about them. Technology then ceases to be a threat, allowing us to magnify our distinctively human capacities of judgment, reasoning, and situational awareness across the battlespace.[66]

These authors seek the inclusion of RPA operators into the larger fold of pilots, emphasizing the Air Force's chosen *RPA* term, to demonstrate that pilotage is more than sitting in the cockpit.[67] Conversely, thinkers such as Houston Cantwell recommend dropping the pilot terminology, along with the stick and rudder, to allow these aircraft to come into their own and realize a potential separate and distinct from that of manned aircraft.[68] He also exposes a hurdle to Blair and Helms's seemingly reasonable approach in that many pilots have wrapped their personal identities so tightly around the act of flying that they will not give it up if asked politely. In fact, one-third surveyed would rather leave the service than fly RPAs.[69] Cantwell, Blair, and Helms would all agree, however, that a concentration on inputs (the stick and rudder) rather than outputs (combat effects) reflects twentieth-century thinking that will not advance airpower.[70]

Regardless of the terminology or approach selected, these cultural issues drive organizational priorities that affect how, when, and even if the Air Force chooses to invest in autonomous technologies. Research on organizational core competencies published in the *McKinsey Quarterly* reveals that "the company's power structure cannot be driven by several functions at once. . . . A world-class competence must steer the power structure in a company. The keeper of the skill drives all the company's major decisions, even in unrelated functions."[71] Although the Air Force espouses three core competencies that enable six distinctive capabilities, in practice it cannot escape the interplay of core competency and power structure.[72] The apparent skill driver in the Air Force is the successful execution of air-to-air combat. Recent commentary from Lawrence Spinetta highlights that leaders in the fighter enterprise have the opportunity to command at 26 wings whereas the RPA enterprise has only one.[73] His interest in the discussion is not about emotive perceptions of fairness; rather, it hangs on Stephen Rosen's observation that the pace of innovation in the military is restricted by the speed at which officers (who, in retrospect, possessed the innovation) rise to consequential levels of the command structure.[74] The concern articulated by Spinetta is that hanging on to fighters so tightly as to slight RPAs (or UCAVs) discards opportunities to preserve the nation's technological edge. Choosing not to respond to FQ-X on the basis of perpetuating the service's power structure could actually nullify the value that structure delivers.

Conclusions

The technological landscape is replete with advances heralding profound change for the means of success in air combat. Nevertheless, certain long-standing discoveries about the nature of airpower itself endure—namely, Boyd's OODA loop and the value of an aircraft's autonomy, whether or not a human is physically aboard. Hyperstealthy metamaterials, carbon nanotube composites, sophisticated computer vision, and advanced AI work in concert to open the door to a new generation of aircraft. These technologies can improve the survivability of human-inhabited vehicles, but combined application in a tactically autonomous system is key to unlocking new levels of performance and economy in air combat. Consideration of cyber and ethical dimensions remains a responsibility of exploring this new potential. Integration with other assets and primacy in the battlespace will prove contentious, particularly since today's RPAs exhibit such constrained performance; however, the notion that all such aircraft will be mere force multipliers for manned fighters represents a potentially tragic underestimation of the capability, efficiency, and lethality of machine pilotage. Functional and subsequent political displacement of the fighter pilot may be an emotionally charged idea, but our developmental priorities must reflect the need to preserve our Airmen, fleet, and sovereignty. Being second to market with tactically autonomous UAVs adds risk. Whether the technology reaches viability next year or in 30 years, its present-day versions prompt us to analyze the logic of their potential. If the machine pilot can usurp the organic one's most prized art form, then that ability raises the question of why any nation would seek a human-inhabited sixth-generation fighter—even if both options were similarly priced.

Aviators may dislike it, the public will question it, science fiction imagines harbingers of the Cylon apocalypse, and we are uncertain about how to best utilize it within the context of a larger Air Force.[75] Nevertheless, the FQ-X concept is too dangerous to our current thinking to ignore forever. The standard rules of the arms race apply: if a rival succeeds first, then our failure would be judged by the words of our own airpower theorists. Just as air superiority is a prerequisite for combined-arms victory, so will tactically autonomous UCAVs (or a novel measure to counter them) become a prerequisite for the survival of fleets of human-inhabited air vehicles. In a technology-dependent service, the cycle of invention, skepticism, resistance, and adaptation continues—all of this has happened before, and all of it will happen again. This particular time, however, it may not matter how undesirable the Air Force culture finds it. Key enabling technologies are evolving outside the military's control. Much of the maturation of unmanned systems occurs with commercial capital to meet civilian business objectives across multiple industries.[76] Creating legal controls is precarious for dual-use technologies that serve principally civil purposes and simultaneously underpin devastating capabilities like FQ-X. Common technical standards obscure the line, and increased computing power raises the stakes for what these systems can accomplish. Ubiquitous dual-use, however, is an opportunity for cost reduction in the development of these aircraft.

Deliberately ignoring tactical machine autonomy may do little to slow its arrival, and for the Air Force, the most proximate threat to resistance may not come from foreign entities but from within the joint team. The US Navy, whose institutional future is tied to its ships rather than what flies off their decks, has outshined its sister services in advancing UAV technology. Common GCS designs, X-47B, and recently opened competition for the unmanned carrier-launched air surveillance and strike system (that awarded four $15 million contracts) show that the Navy is incrementally maturing the technology and concepts.[77] That service will soon have far more impressive UAVs than the Air Force. We might find ourselves right back in the days of acquiescing to the purchase and rebranding of a Navy plane, as with the F-4.[78] ✪

Notes

1. Air Combat Command's (ACC) strategic plan for 2012 omits the terms *UAV*, *UCAV*, *RPA*, or *unmanned* and includes only a single picture of an RQ-4 amidst a collage of other aircraft. Whatever the long-term intent, exclusion in the document reveals that this enterprise is not a first-order priority although the plan clearly states that ACC maintains lead integration responsibilities for global intelligence, surveillance, and reconnaissance and actively seeks to invest in recapitalization, a "Next-Gen fighter," and "a holistic set of game-changing capabilities and cross-cutting technologies" (12). The overall impression communicated is that ACC desires new technology, but it does not convey that remotely piloted systems represent the kind it seeks to develop. Air Combat Command, *2012 Air Combat Command Strategic Plan: Securing the High Ground* (Joint Base Langley–Eustis, VA: Air Combat Command, 2012), especially 3–15, http://www.acc.af.mil/shared/media/document/afd-120319-025.pdf.

2. The Air Force armed the RQ-1 with an AIM-92 Stinger missile in 2002 and fired on an Iraqi MiG that crossed into the no-fly zone but did not win the engagement. Allegedly, a guidance error within the missile prevented it from hitting the MiG. Bootie Cosgrove-Mather, "Pilotless Warriors Soar to Success," *CBS News*, 25 April 2003, http://www.cbsnews.com/news/pilotless-warriors-soar-to-success/.

3. R. A. Shelby, D. R. Smith, and S. Schultz, "Experimental Verification of a Negative Index of Refraction," *Science* 292, no. 5514 (6 April 2001): 77–79, http://www.sciencemag.org/content/292/5514/77; C. G. Parazzoli et al., "Experimental Verification and Simulation of Negative Index of Refraction Using Snell's Law," *Physical Review Letters* 90, no. 10 (14 March 2003): 1–4, http://prl.aps.org/abstract/PRL/v90/i10/e107401; Henri J. Lezec, Jennifer A. Dionne, and Harry A. Atwater, "Negative Refraction at Visible Frequencies," *Science* 316, no. 5823 (20 April 2007): 430–32, http://www.sciencemag.org/content/316/5823/430.abstract; and Debashis Chanda et al., "Large-Area Flexible 3D Optical Negative Index Metamaterial Formed by Nanotransfer Printing," *Nature Nanotechnology* 6, no. 7 (July 2011): 402–7, http://www.nature.com/nnano/journal/v6/n7/full/nnano.2011.82.html.

4. T. Xu et al., "Perfect Invisibility Cloaking by Isotropic Media," *Physical Review A* 86, no. 4-B (October 2012): 1–5, http://link.aps.org/doi/10.1103/PhysRevA.86.043827.

5. AIM-9X (acknowledged) contracts commit to delivery of 10,142 missiles at a cost of $3 billion. "AIM-9X Sidewinder," Deagel.com, 13 November 2013, http://www.deagel.com/Air-to-Air-Missiles/AIM-9X-Sidewinder_a001166003.aspx. AIM-120 AMRAAM program costs exceed $20 billion. "AIM-120D AMRAAM," Deagel.com, 13 November 2013, http://www.deagel.com/Air-to-Air-Missiles/AIM-120D-AMRAAM_a001164006.aspx. Legacy AIM-7 missiles have an advertised unit cost of $125,000. "AIM-7 Sparrow," fact sheet, US Air Force, 1 October 2003, http://www.af.mil/AboutUs/FactSheets/Display/tabid/224/Article/104575/aim-7-sparrow.aspx.

6. “High Energy Liquid Laser Area Defense System (HELLADS),” Defense Advanced Research Projects Agency (DARPA) Strategic Technology Office, accessed 24 August 2013, http://www.darpa.mil/Our_Work/STO/Programs/High_Energy_Liquid_Laser_Area_Defense_System_(HELLADS).aspx.

7. George W. Stimson, *Introduction to Airborne Radar*, 2nd ed. (Mendham, NJ: SciTech Publishing, 1998), 525–34.

8. Ibid., 503.

9. Ibid., 535.

10. Ibid.

11. “CUFFT [CUDA Fast Fourier Transform Library],” nVidia Corporation, accessed 8 August 2013, https://developer.nvidia.com/cufft; and Jimmy Pettersson and Ian Wainwright, *Radar Signal Processing with Graphics Processors (GPUs)* (Uppsala: Uppsala Universitet, February 2010), http://uu.diva-portal.org/smash/get/diva2:292558/FULLTEXT01.pdf.

12. Marc Monthioux and Vladimir L. Kuznetsov, “Who Should Be Given the Credit for the Discovery of Carbon Nanotubes?,” *Carbon* 44, no. 9 (19 March 2006): 1621–23, http://nanotube.msu.edu/HSS/2006/1/2006-1.pdf.

13. X. Wang et al., “Ultrastrong, Stiff and Multifunctional Carbon Nanotube Composites,” *Materials Research Letters* 1, no. 1 (2013): 19–25, http://www.tandfonline.com/doi/pdf/10.1080/21663831.2012.686586.

14. Josh Lowensohn, “Google Snaps Up Object Recognition Startup DNNresearch,” CNet, 12 March 2013, http://news.cnet.com/8301-1023_3-57573953-93/google-snaps-up-object-recognition-startup-dnnresearch/.

15. “About,” OpenCV, accessed 24 July 2013, http://opencv.org/about.html.

16. “OpenCV,” nVidia Developer Zone, accessed 4 August 2013, https://developer.nvidia.com/opencv.

17. The kind of gun targeting system proposed herein would represent the most difficult design challenge after the core artificial intelligence (AI), and it would represent the highest risk item to project success. If the AI fails to meet expectations, the technology might still be transferrable for other less-challenging projects. However, if high-resolution air-to-air gun targeting proves too difficult a problem to solve, then the entire asset must be redesigned to accommodate a different operational construct (e.g., small short-range missiles or a return to conventional radar-guided missiles already in inventory), which may still offer value or may diminish the value proposition substantially. Lessons learned from the software-engineering industry suggest tackling the highest-risk segments of software-intensive systems first through controlled experiments rather than launching into a project via the easiest tasks and later becoming stuck at a point where costs and pressure on the industry team begin to mount. Anthony J. Lattanze, “Architecture Centric Design Method: A Practical Architectural Design Method for Software Intensive Systems,” Carnegie Mellon University, Institute for Software Research, accessed 18 January 2014, http://anthonylattanze.com/acdm.php.

18. Gulshan Luthra, “IAF Decides on 144 Fifth Generation Fighters,” India Strategic, October 2012, http://www.indiastrategic.in/topstories1766_IAF_decides_144_fifth_generation_fighters.htm.

19. Ajai Shukla, “Delays and Challenges for Indo-Russian Fighter,” *Business Standard*, 15 May 2012, http://www.business-standard.com/article/economy-policy/delays-and-challenges-for-indo-russian-fighter-112051502009_1.html.

20. Department of the Air Force, *United States Air Force FY 2011 Budget Estimates,* vol. 1, *Air Force Procurement, Air Force* (Washington, DC: Department of the Air Force, February 2010), 1–15, http://www.saffm.hq.af.mil/shared/media/document/AFD-100128-072.pdf; and Michael Hoffman, "UAV Pilot Career Field Could Save $1.5B," *Air Force Times*, 1 March 2009, http://www.airforcetimes.com/article/20090301/NEWS/903010326/UAV-pilot-career-field-could-save-1-5B.

21. Three billion dollars divided by 10,142 missiles equals approximately $300,000. "AIM-9X Sidewinder."

22. The cost estimate of $9.39 per unit for the PGU-28/B 20 mm semi-armor-piercing high-explosive incendiary round is derived from contract lot size and reported costs. "PGU-27A/B TP/ PGU-28A/B SAPHEI / PGU-30A/B TP-T," GlobalSecurity.org, accessed 31 July 2013, http://www.globalsecurity.org/military/systems/munitions/pgu-28.htm.

23. *The United States Strategic Bombing Surveys (European War) (Pacific War)* (30 September 1945, 1 July 1946; repr. Maxwell AFB, AL: Air University Press, October 1987), 6, 68, http://aupress.au.af.mil/digital/pdf/book/b_0020_spangrud_strategic_bombing_surveys.pdf.

24. Briefing, Col Gary Crowder, subject: Effects-Based Operations, slide 4, "Precision Redefines the Concept of Mass," 19 March 2003, http://www.au.af.mil/au/awc/awcgate/dod/ebo_slides/ebo_slides.htm. In light of deep defense-budget cuts, Hon. Chuck Hagel, the current secretary of defense, observed that the Department of Defense stands again at a crossroads in terms of selecting a small, lean, high-tech force or a larger one that could not afford modernization. Secretary of Defense Chuck Hagel, "Statement on Strategic Choices and Management Review" (speech, Pentagon Press Briefing Room, 31 July 2013), http://www.defense.gov/speeches/speech.aspx?speechid=1798.

25. Richard Fisher, "Deterring China's Fighter Buildup," *Defense News*, 19 November 2012, http://www.defensenews.com/article/20121119/DEFFEAT05/311190005/Deterring-China-8217-s-Fighter-Buildup.

26. John A. Tirpak, "The Sixth Generation Fighter," *Air Force Magazine* 92, no. 10 (October 2009): 38–42, http://www.airforcemag.com/MagazineArchive/Documents/2009/October%202009/1009fighter.pdf.

27. Maj Houston Cantwell analyzed the attitudes of Air Force pilots toward RPAs, finding a significant negative stigma surrounding them. Many pilots appear to love the act of flying more than the leveraging of aircraft to produce military effects. Maj Houston Cantwell, "Beyond Butterflies: Predator and the Evolution of Unmanned Aerial Vehicles in Air Force Culture" (thesis, School of Advanced Air and Space Studies, Maxwell AFB, AL, 2007), 81–85.

28. Corey Sandler, "IBM: Colossus of Armonk," *Creative Computing* 10, no. 11 (November 1984): 298, http://www.atarimagazines.com/creative/v10n11/298_IBM_colossus_of_Armonk.php.

29. Stuart J. Russell and Peter Norvig, *Artificial Intelligence: A Modern Approach*, 3rd ed. (Upper Saddle River, NJ: Prentice Hall, 2010), 695.

30. This article restricts the discussion to air-to-air applications because they present an extremely sterile environment compared to the air-to-ground (surface attack) domain. Acquiring and processing sensor data against a relatively empty background are far simpler than doing so against a cluttered backdrop of Earth's surface and all of the natural and man-made objects layered upon it. Surface attack is also extremely context dependent whereas air-to-air combat follows a more streamlined set of rules regarding electronic and visual identification measures and reconciliation against published rules of engagement. Christo-

pher D. Wickens, "Multiple Resources and Performance Prediction," *Theoretical Issues in Ergonomics Science* 3, no. 2 (April 2002): 168–69, http://www.tandfonline.com/doi/abs/10.1080/14639220210123806.

31. Robert J. Kosinski, "A Literature Review on Reaction Time," Clemson University, September 2013, http://biae.clemson.edu/bpc/bp/Lab/110/reaction.htm; and Andrew G. Barto, Steven J. Bradtke, and Satinder P. Singh, "Learning to Act Using Real-Time Dynamic Programming," *Artificial Intelligence* 72, nos. 1–2 (January 1995): 116–27, http://www.sciencedirect.com/science/article/pii/000437029400011O.

32. During refinement of the concept for this article, Capt Steve Christopher contributed this thought about the sharp contrast between machine preservation of capability and a human's natural tendency to get out of practice without perpetual reinforcement and challenge.

33. Brian Everstine and Marcus Weisgerber, "Reduced Flying Hours Forces [*sic*] Grounding of 17 USAF Combat Air Squadrons," *Air Force Times*, 8 April 2013, http://www.airforcetimes.com/article/20130408/NEWS/304080035/Reduced-flying-hours-forces-grounding-17-USAF-combat-air-squadrons.

34. Col James Jinnette, "Unmanned Limits: Robotic Systems Can't Replace a Pilot's Gut Instinct," *Armed Forces Journal* 147, no. 4 (November 2009): 30–32, http://www.armedforcesjournal.com/unmanned-limits/.

35. Ibid.

36. Defense Science Board, *Task Force Report: The Role of Autonomy in DoD Systems* (Washington DC: Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, July 2012), 33–45, http://www.acq.osd.mil/dsb/reports/AutonomyReport.pdf.

37. James S. McGrew et al., "Air Combat Strategy Using Approximate Dynamic Programming," *Journal of Guidance, Control, and Dynamics* 33, no. 5 (September–October 2010): 1641–54. See also James S. McGrew, "Real-Time Maneuvering Decisions for Autonomous Air Combat" (master's thesis, Massachusetts Institute of Technology, June 2008), 63–86, http://dspace.mit.edu/bitstream/handle/1721.1/44927/309353804.pdf?sequence=1.

38. The current level of maturity supports a Department of Defense Technology Readiness Level (TRL) of three. Assistant Secretary of Defense for Research and Engineering, *Technology Readiness Assessment (TRA) Guidance* (Washington, DC: Assistant Secretary of Defense for Research and Engineering, April 2011), 2–13, http://www.acq.osd.mil/chieftechnologist/publications/docs/TRA2011.pdf.

39. "Microchips That Mimic the Brain: Novel Microchips Imitate the Brain's Information Processing in Real Time," *Science Daily*, 22 July 2013, http://www.sciencedaily.com/releases/2013/07/130722152705.htm.

40. Emre Neftci et al., "Synthesizing Cognition in Neuromorphic Electronic Systems," *Proceedings of the National Academy of Sciences of the United States of America*, 22 July 2013, http://www.pnas.org/content/early/2013/07/17/1212083110.

41. Maj Rene F. Romero, "The Origin of Centralized Control and Decentralized Execution" (thesis, US Army Command and General Staff College, 2003), 58–84, http://www.au.af.mil/au/awc/awcgate/army/romero.pdf.

42. From the author's personal experience and the experience of numerous RPA pilots. Flying the Predator and having the combined force air component commander relay direction to the crew via text chat occurred repeatedly during Operation Unified Protector.

43. Defense Science Board, *Task Force Report*, 1–3.

44. For an article that exemplifies this viewpoint, see Brian E. Finch, "Anything and Everything Can Be Hacked," *Huffington Post*, 15 August 2013, http://www.huffingtonpost.com/brian-e-finch/caveat-cyber-emptor_b_3748602.html.

45. Dr. Robert Dewar, "Software Technologies Boost Safety and Security of UAV System Architectures," *COTS Journal* 15, no. 7 (July 2013): 28–31, http://www.cotsjournalonline.com/articles/view/103461; and Chris Tapp and Mark Pitchford, "MISRA C:2012: New Programming Guidelines for Safety-Critical Software," *Defense Tech Briefs* 7, no. 4 (1 August 2013): 8–11, http://www.defensetechbriefs.com/component/content/article/17022.

46. Charles P. Pfleeger and Shari Lawrence Pfleeger, *Security in Computing*, 4th ed. (Upper Saddle River, NJ: Prentice Hall, 2007), 10–12.

47. Ibid., 559.

48. Warren Strobel and Deborah Charles, "U.S. on Offense in Cyber War: Building Command Center, Hiring Warriors," *Insurance Journal*, 7 June 2013, http://www.insurancejournal.com/news/national/2013/06/07/294731.htm.

49. Fritz Allhoff, Nicholas G. Evans, and Adam Henschke, eds., *Routledge Handbook of Ethics and War: Just War Theory in the Twenty-First Century* (New York: Routledge, 2013).

50. Armin Krishnan, *Killer Robots: Legality and Ethicality of Autonomous Weapons* (Farnham, England: Ashgate, 2009).

51. Ibid., 4–6.

52. Ibid., 2–3.

53. Thomas K. Adams, "Future Warfare and the Decline of Human Decisionmaking," *Parameters* 31, no. 4 (Winter 2001–2): 57–71, http://strategicstudiesinstitute.army.mil/pubs/parameters/Articles/01winter/adams.htm.

54. Matthew S. Larkin, "Brave New Warfare: Autonomy in Lethal UAVs" (thesis, Naval Postgraduate School, March 2011), 17–38, http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA543725.

55. MSgt Louis A. Arana-Barradas, "Black Hawk Incident 'Tragic Series of Errors,'" Air Force News Service, [1995], http://userpages.aug.com/captbarb/blackhawk.html.

56. Rolf O. Peterson and Paolo Ciucci, "The Wolf as a Carnivore," in *Wolves: Behavior, Ecology, and Conservation*, ed. L. David Mech and Luigi Boitani (Chicago: University of Chicago Press, 2003), 119–21.

57. During refinement of the concept for this article, Capt Jon Kinsey contributed this thought about air vehicle autonomy through the eyes of a terminal attack controller.

58. Joint Publication 3-09.3, *Close Air Support*, 8 July 2009, xv–xvi.

59. Caitlin H. Lee, "Embracing Autonomy: The Key to Developing a New Generation of Remotely Piloted Aircraft for Operations in Contested Air Environments," *Air and Space Power Journal* 25, no. 4 (Winter 2011): 85–86, http://www.airpower.maxwell.af.mil/airchronicles/apj/2011/2011-4/2011_4.asp.

60. Defense Science Board, *Task Force Report*, 1–7.

61. Anthony C. Cain, "L'Armée de l'Air, 1933–1940: Drifting toward Defeat," in *Why Air Forces Fail: The Anatomy of Defeat*, ed. Robin Higham and Stephen J. Harris (Lexington: University Press of Kentucky 2006), 54.

62. "Making Connections at 45,000 Feet: Future UAVs May Fuel Up in Flight," Defense Advanced Research Projects Agency (DARPA), 5 October 2012, http://www.darpa.mil/NewsEvents/Releases/2012/10/05.aspx. Budget constraints prompted the Navy to use manned surrogates to test the data-link system for autonomous air-to-air refueling; however,

that service believes it will get the same level of technology maturation through the reduced-cost approach. Graham Warwick, "X-47B Unmanned Aerial Refueling Demo Victim of Cuts," *Aviation Week*, 15 April 2013, http://www.aviationweek.com/Article.aspx?id=/article-xml/asd_04_15_2013_p03-01-568738.xml.

63. Chair flying is a practice among pilots to study and prepare for a flight whereby they mentally rehearse and visualize the sequence of events that they expect to happen during the actual flight.

64. Col Michael W. Pietrucha, "The Next Lightweight Fighter: Not Your Grandfather's Combat Aircraft," *Air and Space Power Journal* 27, no. 4 (July–August 2013): 40, http://www.airpower.au.af.mil/digital/pdf/issues/2013/ASPJ-Jul-Aug-2013.pdf.

65. Maj David J. Blair and Capt Nick Helms, "The Swarm, the Cloud, and the Importance of Getting There First: What's at Stake in the Remote Aviation Culture Debate," *Air and Space Power Journal* 27, no. 4 (July–August 2013): 18, http://www.airpower.au.af.mil/digital/pdf/issues/2013/ASPJ-Jul-Aug-2013.pdf.

66. Ibid., 22, 23.

67. Ibid., 29.

68. Cantwell, "Beyond Butterflies," 115.

69. Ibid., 86.

70. This perspective of focusing on effects is also central to former Air Force chief of staff Gen John P. Jumper's vision of future RPA concepts of operations. Gen John P. Jumper, USAF, retired, "Next Generation Remotely Piloted Vehicle Concept of Operations" (unpublished), 14 March 2011, provided via e-mail by Capt Curt Wilson, USAF.

71. Patricia Gorman Clifford, Kevin P. Coyne, and Stephen J. D. Hall, "Is Your Core Competency a Mirage?," *McKinsey Quarterly*, no. 1 (1997): 48–49, http://www.mckinseyquarterly.com/article_page.aspx?ar=186.

72. "Our Mission," United States Air Force, accessed 1 August 2013, http://www.airforce.com/learn-about/our-mission/.

73. Lt Col Lawrence Spinetta, "The Glass Ceiling for Remotely Piloted Aircraft," *Air and Space Power Journal* 27, no. 4 (July–August 2013): 107, http://www.airpower.au.af.mil/digital/pdf/issues/2013/ASPJ-Jul-Aug-2013.pdf.

74. Stephen Peter Rosen, *Winning the Next War: Innovation and the Modern Military* (Ithaca, NY: Cornell University Press, 1991), 105.

75. In Glen A. Larson's 1978 television series *Battlestar Galactica*, later remade in 2003 by Ronald D. Moore and David Eick, Cylons were intelligent machines that achieved self-awareness and rebelled against humanity; they were the antagonists of the story line.

76. For example, the Association of Unmanned Vehicle Systems International's 2013 Unmanned Systems Conference and Exhibit enjoyed 75 percent commercial/industrial attendees versus 16 percent military. "Why Attend?," AUVSI's Unmanned Systems 2013, accessed 22 August 2013, http://www.auvsishow.org/auvsi13/public/Content.aspx?ID=1242.

77. Michael Cooney, "When Open Source and Drones Mix: US Navy Better Than Army and Air Force," *Network World*, 8 August 2013, http://www.networkworld.com/community/node/83576; and Tamir Eshel, "US Navy Awards UCLASS Studies amid Debate on Performance," *Defense Update*, 21 August 2013, http://defense-update.com/20130821_us-navy-awards-uclas-contracts-amid-debate.html.

78. "F-4 Phantom II Fighter," Boeing Corporation, accessed 23 August 2013, http://www.boeing.com/boeing/history/mdc/phantomII.page; and Capt Curt Wilson, personal e-mail

correspondence, 18 August 2013. Captain Wilson predicts that the Air Force, strained by severe budget limitations and frustrated in its attempts to innovate amidst high operations tempo, will likely accept the US Navy's lead on RPAs in the short term.

Capt Michael W. Byrnes, USAF

Captain Byrnes (USAFA; MS, Carnegie Mellon University) recently arrived at the 29th Attack Squadron, Holloman AFB, New Mexico, to serve as an MQ-9 Formal Training Unit instructor pilot. Previously, he was a dual-qualified MQ-1B pilot and an MQ-9 instructor pilot working in the weapons and tactics section of his last squadron at Creech AFB, Nevada. He has flown more than 2,000 hours of diverse mission sets in the MQ-1 and MQ-9 in support of worldwide contingency operations. A graduate of the Euro-NATO Joint Jet Pilot Training Program and a distinguished graduate of the Air Force Academy, Captain Byrnes served as an enlisted avionics-sensor-maintenance journeyman prior to commissioning.

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