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The Last Manned Fighter

Replacing Manned Fighters with Unmanned Combat Air Vehicles

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Disclaimer

Foreword

It is my great pleasure to present another of the *Wright Flyer Papers* series. In this series, the Air Command and Staff College (ACSC) recognizes and publishes our best student research projects from the prior academic year. The ACSC research program encourages our students to move beyond the school's core curriculum in their own professional development and in "advancing air and space power." The series title reflects our desire to perpetuate the pioneering spirit embodied in earlier generations of Airmen. Projects selected for publication combine solid research, innovative thought, and lucid presentation in exploring war at the operational level. With this broad perspective, the *Wright Flyer Papers* engage an eclectic range of doctrinal, technological, organizational, and operational questions. Some of these studies provide new solutions to familiar problems. Others encourage us to leave the familiar behind in pursuing new possibilities. By making these research studies available in the *Wright Flyer Papers*, ACSC hopes to encourage critical examination of the findings and to stimulate further research in these areas.

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Abstract

This paper addresses the question, can and should the Air Force pursue an unmanned multirole fighter to *replace* manned systems? Unmanned aircraft systems have demonstrated enormous intelligence, surveillance, and reconnaissance (ISR) capabilities in both flexibility and persistence. Current and emerging technology may permit unmanned fighters to replace conventional multirole aircraft in the face of high endurance missions, evolving threat systems, and political pressure to preserve human life.

This research is framed in the context of a specialized weapon in military aviation: an unmanned multirole fighter capable of replacing manned systems and their respective missions. This paper gives a brief history of unmanned aerial vehicles and their employment as weapons to demonstrate the evolution from ISR platform to unmanned combat air vehicle and then evolves into two main sections of "can we" and "should we" pursue this avenue of development. The primary means of answering the research question is both technical and philosophical. Before being able to answer if the Air Force *should* pursue an unmanned fighter, it is necessary to determine if it is technically *feasible* for such a system. A methodical analysis of mission subsets and common tasks that fighters currently perform and how those tasks might be performed in an unmanned vehicle are examined to substantiate technical capability. Inherent to this discussion are the obvious questions of remote piloting versus autonomous operations, command and control, and weaknesses that may be presented to an adversary. Modern media, political costs of human life, single points of failure, command and control, and monetary costs are then addressed to develop the subjective main point of pursuing acquisition.

The range and endurance of unmanned combat air vehicle (UCAV) fighters offer persistence and attractive options in a world of growing antiaccess strategies. They offer advantages in performance, altitude, and employment without the limitations of human physiology. UCAV fighters

deny the political use of prisoners of war by our adversaries and preserve the tactical knowledge of our pilots at home.

The research finds there are no technological barriers that prohibit the design and use of UCAV fighters on a large scale. There are anticipated limitations in bandwidth and concern for performance during within-visual-range maneuvering if man-in-the-loop is the solution to command and control. Ultimately, UCAV fighters are not a panacea but offer the presence of force in a threat environment that 20 years from now will be extremely lethal. The costs and risks associated with UCAV fighters are significant but surmountable. The single point of failure may be in our command and control through the radio frequency spectrum. Autonomy provides a solution but is incompatible with US ascription to the law of armed conflict and its mandates. If sufficient bandwidth can be secured and the control of remote vehicles can be assured, there are immense dollar and political costs to be saved in their employment. In the context of future threat systems and antiaccess strategies, the Air Force would be foolish not to pursue UCAV fighter technology.

Preface

This paper examines the potential use of unmanned aerial vehicles (UAV) as multirole fighters in both unmanned and autonomous capacities. Previous research in the field of UAVs and unmanned combat air vehicles is widely available and tends to focus on specific mission sets such as intelligence, surveillance, and reconnaissance or suppression of enemy air defenses while quickly dismissing UAVs as multirole fighters. The focus of this research is to demonstrate the technical feasibility of unmanned fighters across multiple mission sets and is, therefore, inherently broad in scope. The goal is to consolidate proven concepts and capabilities, address those capabilities with subjective questioning, and determine the likely future of unmanned fighters in our combat air forces (CAF).

This paper assumes the reader has a basic understanding of unmanned aerial systems (UAS), close air support (CAS), air interdiction (AI), and similar tasks/mission sets attributed to multirole fighters, as well as the lexicon of the CAF community.

The author is an Air Force pilot with 14 years of service, formerly a command and control officer, AC-130H navigator, F-15C four-ship flight lead, and F-4F instructor pilot, and has served as project officer for Air Force Doctrine Document 2-1.3, *Counterland Operations*, at the Air Force Doctrine Center, Maxwell AFB, Alabama.

I would like to thank Lt Col Anthony Gould, my ACSC faculty research advisor, for his guidance and assistance in bounding this effort. I would also like to thank Maj Ernest Teichert for his expertise on the F-22 and Maj Rob Preston from the Air Force Judge Advocate General School for his contributions regarding the law of armed conflict. Finally, I'd like to thank Lt Col "Skid" Greene, 42d Attack Squadron commander, for his assistance in obtaining unclassified details regarding command and control of UAVs, specifically with regard to command delay.

Introduction

There is a tendency in our planning to confuse the unfamiliar with the improbable.

—Thomas Schelling

The notion of unmanned fighters patrolling the skies of future battlefields is intriguing to some and heresy to others but should not be confused with the improbable. Advances in communications technology, microprocessors, artificial intelligence, and weaponry now permit unmanned systems at costs and lethality previously thought unattainable. Unmanned aerial vehicles (UAV) have been used for many years in warfare but only recently have demonstrated such enormous success in the intelligence, surveillance, and reconnaissance (ISR) realm that their potential use in combat systems has gained real interest and momentum in the United States. The latest addition to the growing UAV fleet in the US military is the MQ-9 Predator B, boasting an external payload of 3,000 pounds and supported by synthetic aperture radar (SAR) and forward-looking infrared (FLIR) sensors.[1] The MQ-9 is pushing the leading edge of UAV technology as a combat vehicle and is just a few steps short of an unmanned multirole fighter. The MQ-9 can be armed with Joint Direct Attack Munitions (JDAM) as well as the Air Intercept Missile (AIM)-9X air-to-air missiles but is confined to an airframe designed for endurance with high-aspect-ratio wings and a turboprop power plant. Such demonstrated capability begs the question of the practicality and utility of an unmanned jet fighter, commonly regarded as too complex and demanding a mission for a machine alone—the last bastion of the fighter pilot.

UAVs had a more humble beginning, of course; the first UAV designed for warfare was the "Kettering Bug" in World War I.[2] The Bug was little more than a flying bomb whose propeller would stop turning after a preset number of revolutions—the wings would literally fall off, and the Bug would drop unguided to the earth. Based on rudimentary calculations of speed versus time, the Bug could be set to drop at an approximate distance, albeit with some margin of error.

Entire books are devoted to the evolution of UAVs, but there are at least two fundamental themes to be drawn from the pursuit of such programs. First, UAVs are not born of fanciful design but *mission requirements*; in the case of the Bug, an unguided bomb with a range of 50 miles was called for.[3] The arming of an MQ-1 Predator by the Central Intelligence Agency was not a novelty but born of the need for a high-endurance ISR asset with the capability to destroy a fleeting target, as done in November 2002, killing suspected al-Qaeda terrorist Ali Qaed Sinan al-Harthi (also known as Abu Ali).[4] Second, the failure of such programs in the past is largely attributed to cost overruns and failure to *meet* mission requirements as outlined by the armed services.[5]

If the Air Force can replace manned fighters with unmanned combat air vehicles (UCAV) *and* meet mission requirements at lower costs, why risk the presence of aircrew over hostile territory? The preeminence of UCAVs should be viewed through the variables of costs, risks, and capabilities; what can the Air Force get, at what cost, and at what risk? It is practical to outline this research in this context, but it is more appropriate to address the technical requirements of unmanned fighters before examining if the Air Force should pursue replacing manned cockpits with machines. *Specifically, can an unmanned fighter do what manned fighters do, and should the Air Force engage in such an enterprise based on costs, risks, capabilities, and other underlying factors?*

The next section addresses technical requirements for an unmanned fighter based on the tactics and procedures used in its manned equivalent, followed by a second section that examines costs, capabilities, and limitations of unmanned fighters. Finally, a recommendation is made based on what the data supports and the philosophical answers point towards. Ultimately, there is an opportunity cost to pursuing *or not* pursuing this technology, and if it is technically possible to employ UCAV fighters, the time to answer the acquisition question is now.

Technical and Mission Requirements

Modern fighters engage in a variety of missions but share common mission tasks that must be met in order to perform tactically. These tasks include cooperative employment, formation flight, aerial refueling, and target identification. These tasks provide for air interdiction (AI), close air support (CAS), and counterair missions, holding within-visual-range (WVR) and beyond-visual-range (BVR) engagements as a baseline. For the unmanned fighter, however, it is first necessary to address command and control (C2) of the aircraft.

Command and Control

The issue of command and control is addressed throughout this paper; it is paramount because it not only provides a potential single point of failure for the unmanned aerial system (UAS) but also because it is one of perhaps two of the most challenging areas for meeting manned-equivalent tasks. UAVs are either remotely controlled by a human while in flight, also known as man-in-the-loop (MITL), or they are preprogrammed to carry out a mission and return to base (autonomous). Both forms of control are more thoroughly addressed in the philosophical section of this research, but for the technical question at hand, it has been proven repeatedly that unmanned fighters can be reliably controlled or preprogrammed to carry out assigned tasks. Unmanned F-6F Hellcats were flown from 1946 to 1948,[6] and unmanned QF-4s are still flown today from Holloman and Tyndall Air Force Bases as target drones. The Global Hawk, roughly the weight of an unarmed F-16, flies profiles in excess of 28 hours autonomously. QF-4s are flown MITL and in the event of data-link failure revert to preprogrammed profiles, but this doesn't solve the unmanned fighter problem so easily. QF-4s are generally flown in formations of two; if the Air Force seeks to replace manned machines with UCAV fighters, it is necessary to control large formations such as strike packages simultaneously, and this requires both *bandwidth* and *cooperative employment*.

The problem of *bandwidth* can be solved in one of at least two ways. Data can be processed locally on the UAV from partial to complete autonomy, or data must be squeezed into the finite radio frequency (RF) spectrum for transmission to and from the ground station controlling it. Complete autonomy has its own disadvantages but is an instant solution to bandwidth requirements. Naturally this would require a high degree of problem-solving capability and reliable heuristics for a machine to generate a desired behavior, but the technical aspect was proven in 1989 when the UA (unmanned aircraft) Condor accomplished a completely autonomous flight from takeoff to landing.[7] Any degree of MITL requires transmissions through the RF spectrum, now accomplished via the Kurtz-under (Ku) band for the Predator and Global Hawk,[8] but technology affords nearly limitless bandwidth for transmitters/receivers with requisite sensitivity. Consider two radio stations of 98 megahertz (MHz) and 99 MHz, with a third squeezed in at 98.5 MHz. If the radio station can focus a transmission well enough and the receiving radios are sensitive enough to pick it out, nothing prevents data from being transmitted on 98.5 MHz as well as 98.5*125* MHz or 98.512*5050*, and so forth. Naturally, this may require both power to overcome range and background noise and money for expensive equipment—but the point is it's possible with current technology, complemented by future advances in compression and cryptology. Technology aside, determining what frequencies (Ku or otherwise) are allotted to C2 becomes a simple matter of RF requirements and priorities in-theater. Manually controlling a single UCAV that leads others in battle would reduce bandwidth requirements proportional to the size of the formation considered. Again, the point is that large-scale control of UCAV fighter formations is technically possible, even more so if UAV formations have a leader/follower relationship and operate cooperatively.

Cooperative Employment

Cooperative employment, the second half of the C2 problem as well as a common fighter task, has also been successfully demonstrated. As previously mentioned, the QF-4 target drone is regularly flown in formation and can take off/land in nearly the same timing and proximity as manned fighters. In February of 2007, "a single SkyWatcher UAV successfully demonstrated cooperative flight with three simulated SkyWatchers, each UAV performing a different role and operating a unique sensor package."[9] It is the software, of course, that allows autonomous vehicles to operate cooperatively and even complementarily. Dynamic programming (DP)[10] and "high order sliding modes"[11] have demonstrated the ability of UAVs not only to deconflict or coordinate but to *cooperate* against target sets, maximizing available weapons for the greatest effect, the effect of successive weapons, and survivability of the UAV formation itself. This technology holds great promise for autonomous weapons employment but has obvious legal implications without MITL and is addressed in the second half of this paper. In sum, the bandwidth and cooperative employment tools necessary are available to keep MITL or autonomous UCAV fighters aloft for extended durations. Lacking the high-aspect-ratio wings of ISR UAVs, however, UCAV fighters will need to air refuel as their manned counterparts do.

Air Refueling

Manned fighters must air refuel often; it is a byproduct of limited fuel storage capacity, high fuel burn rates, wing forms optimized for speed rather than endurance, and requisite maneuverability. If UCAV fighters are to replace manned fighters, they must be able to air refuel safely and expediently. Modern commercial and some military aircraft can land themselves by electronic guidance and regularly do so more precisely than human operators. Landing with zero visibility and cloud cover at the surface is facilitated by a radar altimeter, electronic flight controls, and a combination of electronic guidance telling the airplane lateral and vertical displacement relative to a predetermined flight path outlined by RF transmissions. It should come as no surprise then that it isn't difficult for a UAV to maneuver itself into a relatively static position in space in order to air refuel using the same type of electronic guidance. The three key steps to air refueling are making the rendezvous, determining refueling order, and the air refueling itself. The rendezvous is perhaps the simplest process as it is already very regimented and predictable—ideally suited for automated guidance that is supported by on-board radar; identification, friend or foe (IFF); and air-to-air tactical navigation (TACAN). Tankers and receivers have preset altitudes, times, and turn points; this is a predictable structure easily navigated by UCAV autonomy. After all, relying on computers to calculate rates, angles, distances, and times is the foundation of modern flight-management systems. The simplicity of this process is demonstrated every time two QF-4s are maneuvered into formation following separate takeoffs. The greatest difficulty is determining the refueling order for a given number of receivers based on time constraints, fuel levels, or other mission priorities. Normally, this is solved verbally between flight leads and the tanker. This could still be done with MITL UCAVs, but autonomous UCAVs would require additional DP to resolve priorities. Research supported by the AF Office of Scientific Research has demonstrated that DP algorithms are possible to determine and control the flow of UCAVs in the receiver chain while minimizing shuffling of priorities as UCAVs join and leave the tanker cell.[12] Once prioritized for refueling, control of the UCAV during refueling could be done MITL from a ground station or second boom operator or autonomously. In August of 2006, Boeing demonstrated its automated aerial refueling program when a UAV Learjet maintained refueling formation with a KC-135R for multiple orbits.[13] Later, in August of 2006, the Defense Advanced Research Projects Agency configured a NASA F/A-18 for an unmanned test (with a safety pilot aboard) and successfully took fuel using the probe/drogue basket method, guided into the contact position using optical sensors and the global positioning system (GPS).[14] Unmanned air refueling technology is immature, to be sure, but the technology exists now, is advancing rapidly, and can't be considered prohibitive for UCAV fighter acquisition. Just getting to the fight isn't enough, of course. Air refueling provides for range, endurance, and payload, but to engage targets UCAVs will need to be capable of target identification.

Target Identification and Engagement

As with previous topics, this problem has several parts; static and emerging targets may be loaded into fire-control computers or uploaded via data link, but some targets will have to be identified as friend or foe in dynamic environments.

Static targets, the simplest of four possible cases, are common to AI missions and cruise-missile profiles. MITL and autonomous UCAVs are virtually identical to manned fighters when it comes to flying to a point in space, slewing a targeting pod to a point on the Earth, confirming the target, and dropping a weapon. There is no requirement for a pilot to be *in the cockpit* vice a ground station, although the latter adds the burden of bandwidth. With ranges around 15 nautical miles, aircrew in the cockpit today may never see the JDAM target they are attacking. Like the cruise missile and JDAM, an autonomous UCAV is authorized at *launch* to seek out a set of coordinates. In this mind-set, even autonomous UCAVs are capable of destroying static targets. At best, they are preprogrammed like cruise missiles. At worst, targets are confirmed via video piped to a ground station, but the process remains largely unchanged.

Identifying dynamic targets in air-to-air *at long range* is equally feasible. Manned fighters identify hostile aircraft BVR using on-board electronic ID and inputs from off-board sources (Airborne Warning and Control System, Rivet Joint, data-link networks—Link16, situation awareness data link, etc.). Target ID is not accomplished directly by the human in the cockpit and therefore permits UCAV substitution. Discussion of morality, responsibility, and authority to kill aside, there is no technical reason prohibiting UCAV fighters from engaging in BVR combat.

Identifying dynamic targets in air-to-air *at close range* is more difficult but also possible with current technology. If an opposing aircraft is able to merge with friendly fighters without being identified, it is often up to the human in the cockpit to determine friend or foe status. Relative closure and angular changes between aircraft can preclude the use of electronic systems, and pilots revert to the "Mark 1 Eyeball" for positive ID (PID). Therefore, if the human eye is the sole means of PID in such an engagement, technology must be able to replicate that function and transmit it to a ground station for MITL, or the UCAV must make its own decision if autonomous. As before, technology has already overcome this hurdle; clearly, the supremacy of modern optics over the human eye is beyond question, but what is seen, the speed with which it can arrive at a decision point, and what is interpreted is critical. Synthetic vision can be accommodated by multiple cameras as hosted on the F-35 Joint Strike Fighter (JSF). The JSF's distributed aperture system (DAS) "consists of multiple infrared [IR] cameras providing 360° coverage using advanced signal conditioning algorithms."[15]

The DAS provides day/night vision in a digital stream that can be interpreted either on a helmet display in manned systems, piped to a ground control station for MITL, or interpreted by software in autonomous UCAVs (fig. 1).

Figure 1. F-35 DAS. (Reprinted from Lockheed-Martin briefing, "JSF Capability Brief" [Air War College, Maxwell AFB, AL, 24 October 2006].)

The speed with which the human eye moves this data is roughly that of an old network card, 10 megabits per second,[16] whereas most US households today host computers with 10/100 mega bit network cards. Clearly our technology is beyond this stage, and even the data from six DAS cameras is captured and moved efficiently through the F-35 military data bus. This information must be interpreted, however, and in the case of MITL remains at a ground station and subject to the inherent strengths and weaknesses of human vision. If autonomous, target identification must rely on a database for comparison and will require detailed imaging of anticipated adversaries. The AIM-9X Sidewinder missile hosts an imaging IR seeker that combines visual and IR spectrums for target ID and greater counter-countermeasure capability.[17] Identifying the aircraft itself, vice a prominent heat source, aims to improve probability of kill but demonstrates the advanced state of imaging technology (fig. 2). Charge-coupled device cameras and IR sensors like the combined seeker of the AIM-9X provide for autonomous ID of aircraft type, and MITL brings image processing to the ground control station of a UCAV fighter. Therefore, current technology demonstrates the capability to acquire imaging as fast as the human eye, move that data at speeds greater than the human eye, and interpret it via database or MITL to achieve the same end state as the human operator in the cockpit. The technical aspects of WVR target ID in air-to-air cannot be considered prohibitive for the fighter UCAV.

Figure 2. AIM-9X seeker head and digital imaging. (Reprinted from "Aim 9-X," *Jane's Defence* online [accessed via Air Command and Staff College subscription], http://www4.janes.com.)

Discriminating between *dynamic targets on the ground* as found in CAS scenarios can be more difficult than BVR or even WVR air engagements, as air-to-air targets reside in a sterile environment compared to the chaos of close-quarters ground combat. The capabilities of fighters that support CAS missions, such as the F-16, F-15E, and A-10, must be transferable if the Air Force seeks to replace these manned aircraft with UCAV fighters. As discussed in target ID technical requirements, optical *range and resolution* used in modern sensors outperform the human eye and allow the analysis of additional spectrums aside from visible light (fig. 3).

Figure 3. Global Hawk imagery from approximately 60,000 feet. (Reprinted from Wright-Patterson AFB, Aeronautical Systems Center [ASC/RAVP].)

Targeting pods, in combination with SARs, deliver high-quality imagery to the cockpit or UCAV ground station but in comparison to the human eye have a very narrow field of view. The MQ-1 predator ultra-wide field of view is 34° x 45°[18] as compared to the human eye, which is 180° x 90° in binocular vision.[19] Even so, existing technology in the Global Hawk as well as the F-35 JSF provides the level of detail required for CAS, and SAR imagery allows targeting in all weather conditions where laser-guided munitions may be degraded or unsuitable due to cloud cover (fig. 4). To enhance available technology, advances in synthetic vision promise to supplement human vision with computer-generated graphics, overlays that both ease bandwidth requirements and hope to improve situational awareness of UCAV pilots.[20]

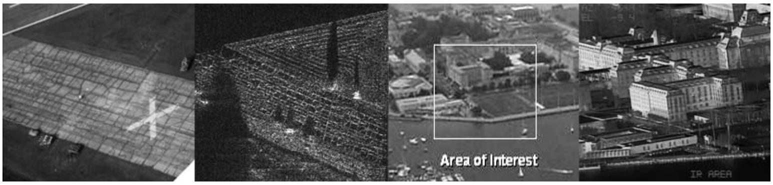

Figure 4. F-35 Targeting. (Reprinted from Lockheed-Martin briefing, "JSF Capability Brief" [Air War College, Maxwell AFB, AL, 24 October 2006].)

None of the four categories of static, air-to-air (BVR), air-to-air (WVR), or dynamic ground targets prove to be beyond the capacity of existing technology for target identification. The Air Force's procedural instruction for the tactical employment of unmanned aircraft systems,[21] published in 2006, serves to reinforce the UCAV coming of age *in support* of CAS. UAVs are shown to provide situational awareness and target identification in support of manned fighters. The optics available and the ability to see outside the visible light spectrum introduce the ability to see RF "tags" or IR strobes used to identify friend from foe. The same end is achieved now with bulky night vision goggles and interpreting FLIR targeting pods. Nothing precludes a UCAV fighter from accomplishing the mission with its own sensors and weapons to find, fix, track, target, engage, and assess the enemy in CAS.

While CAS is very challenging, to be sure, UCAV fighters are quickly dismissed in the role of air-to-air superiority due to the extremely dynamic art and science of WVR maneuvering, also known as the dogfight. Close-range air-to-air engagements have been exceedingly rare since Desert Storm, yet the Air Force learned long ago that there is always a need for close-range capability. The missiles of Vietnam didn't make the gun of previous generations obsolete; even the high-tech F-22 maintains an internal canon for close-range engagements. The lesson is that dogfights will happen. When they do, the UCAV fighter must be able to respond, survive, and kill as well as its manned equivalent. This is no small task considering the speed and durations involved in dogfighting, where even the smallest misjudgment can prove fatal. Once again we revisit the two cases of MITL versus autonomous control and find technical options.

For MITL, the greatest problem is C2 delay, which approximates two seconds from command-input to command-executed by the remote vehicle.[22] In other words, the remote pilot is reacting to what he sees, but that data is two seconds old. Prior to the merge, a two-second advantage equates to no less than about a four-nautical-mile lead time for an opponent to fire an equally capable weapon. Post-merge, at a nominal turn rate of 15 to 18 degrees per second—a two second advantage given to the adversary from an otherwise neutral pass—will land the friendly UCAV at a 30 to 36 degree geometric disadvantage. This, of course, is wholly unacceptable in today's world of high-off-boresight weapons and helmet-mounted sights with "look and shoot" capability (see fig. 5).

Figure 5. Lead turn by enemy fighter exploited to achieve nominal weapon engagement zone (WEZ)

The AIM-9X air-to-air missile WEZ is superior to the Soviet short-range AA-11, but this advantage is only recent and may be fleeting as other countries develop similar capabilities. If MITL is to be employed WVR, UCAV fighters will have to rely on superior *training, weapons, or maneuverability* to outperform near-peer adversaries. Fortunately, we maintain a global advantage in all cases while UCAV fighters promise even greater maneuverability without the frail human pilot. Maneuvering above roughly 10Gs will normally cause gravity-induced loss of consciousness in a manned fighter whereas unmanned fighters are limited only by structural design. UCAV fighters have the potential for maneuvering up to the load limit of turbine engines. Until different or more durable engines can be designed, the current limit is speculated to be about 20Gs.[23] However, such maneuverability may only be useful in an end-game defensive maneuver, as such turn rates come at huge expense to airspeed and lift. When combined with an unpredictable orthogonal roll, this maneuvering will drive missiles to abandon lead-pursuit trajectories and fall back to pursuit geometry, for which high-G maneuvering may prove good enough to survive. If the initial merge can be survived, follow-on maneuvering with MITL is virtually the same as if done from within the cockpit, using sensors such as DAS or FLIR to provide vision. The human operator is then responsible for maneuvering at the sizeable disadvantage of a two-second delay in C2.

The notion of autonomous maneuvering in a dogfight is sure to cause a great deal of debate in the fighter community, but none can deny the regimented and scripted process that pilots train to during basic fighter maneuvers (BFM). There is no shortage of lists and priorities in any BFM training brief, and the repetitive structure has great utility for learning tactics and generating a decision matrix required for split-second reactions in combat. Such lists and priorities are also ideal for automation, which a computer can navigate and forecast much faster than a human being. This is illustrated in the following sample human decision matrix for BFM, following a bandit in the vertical (i.e., vertical jinks):

- Pull to bandit point of departure, and set weapons to combined mode (Gun/Aim-9).
- Assess your altitude and airspeed.
- If no room to go vertical then begin oblique maneuver (exit matrix).
- If room to follow then set your power to reach the control zone and continue.
- Begin your follow-on.
- Seek an optimum range inside the control zone of 2,500 to 3,000 feet.
- If you are too close—go later, with line-of-sight away to increase range.
- If you are too loose—go earlier, cutting the corner to reduce range.

It is ironic that dogfighting is sometimes referred to as a game of chess—move and countermove—as 10 years ago a computer (dubbed "Deep Blue") beat world champion Garry Kasparov in a six-game tournament.[24] Modern personal computers and retail software are able to "look ahead" much further than their human counterparts for possible outcomes based on the present. This, of course, is exactly what fighter pilots do—assess range and angles to the enemy fighter; assess enemy intentions based on energy depleted, plane of motion, and angular change; assess their own position in space and weapons capability; and make a decision for maneuvering. Provided the UCAV fighter can maintain "sight" of the enemy fighter, it is capable of doing all of the above, faster than a human pilot, and can apply flight controls more precisely to achieve the required geometry to achieve a WEZ.

Human pilots are susceptible to common errors such as poor assessment of the enemy fighter (eyesight), improper plane of motion (lift vector placement), pulling too hard or not enough (energy mismanagement), improper prioritization (task management), intimidation (bleed energy when not required), and so forth. Computer algorithms, on the other hand, are subject only to their programming and the input their sensors provide, for better or worse. A great deal can be learned from watching a computer play chess against itself; computer algorithms for BFM can be improved and adapted in much the same manner. As with Kasparov, fighting against the best human fighter pilots and subsequently against its own algorithms, automated BFM can provide for superior maneuvering against the majority of the pilots the world over. Although Kasparov defeated Deep Blue in early matches, the computer was reprogrammed to anticipate how he fought and became invulnerable to his traps. Such lessons for UCAVs are easily transferable code—replicated in hours fleet-wide if necessary, versus the years of experience and hundreds of flight hours required to produce a single human combat veteran.

Technical and Mission Requirements Summary

Existing technology has demonstrated the capacity to perform the essential tasks that current manned fighters engage in. UCAV fighters have the potential to operate cooperatively both in formation and in aerial refueling operations. In combat they can identify friend from foe in static and dynamic scenarios against targets in-flight and on the ground. They are capable of conducting simple profiles such as AI as well as complex tasks such as CAS and WVR maneuvering. They have a greater degree of survivability due to exclusive high-performance maneuvering and, combined with algorithms defined from mathematics and human experience, are *all* capable of being the most experienced pilot the United States has to offer. As we have seen, however, none of these capabilities comes without a price or trade-off. What then are the subjective reasons the Air Force must consider in pursuing *or not* pursuing unmanned fighters?

Analysis

> *If it weren't for the novelty of not having a man in it, would we even be thinking about this vehicle?*
>
> —Gen John P. Jumper
> Former USAF chief of staff

As mentioned at the outset of this paper, weapon systems are usually acquired by the military to fill a mission requirement. Traditionally this has meant bringing a capability to the fight that soldiers, sailors, marines and Airmen need—*and know* they need. Alternatively, history has demonstrated that new technologies developed outside the military have great potential for the armed forces, if only we knew how to best apply them. UAVs in the ISR role have demonstrated their vast potential in Iraq and Afghanistan and are only now making their way into service and joint doctrine. What the USAF calls "best practices" the Army often calls "validated." In other words, you have to demonstrate that a new system can fill a role before it will be accepted in that role, be it as a replacement or augmentation. Only then will its use be scripted and written into doctrine. This is an important concept, as noted by Dr. Richard Hallion a full 20 years ago at Wright-Patterson Air Force Base: "Mere technological superiority could not, on its own, drastically reshape military events. Rather, such superiority had to be coupled with appropriate doctrine in order to generate a kind of catalyst to change." In his article on doctrine and technology, Hallion cites the pre–World War II convictions of Great Britain that the submarine was only a coastal defense weapon and "ignored [as an] offensive potential."[25] With the rise of the UAV in ISR, we also cannot ignore the first uses of airplanes in World War I for reconnaissance. The natural progression seems to be to validate new technology in support roles before it moves to more critical roles in combat. What then can a UCAV fighter *do* that manned fighters cannot, at what risk, and at what cost? This ultimately determines the opportunity cost of pursuing or not pursuing UCAV fighter technology and corresponding doctrine.

Capabilities and Advantages

Perhaps the primary benefit of the UCAV fighter is as deceptively simple as it is profound; there is no human in the aircraft. Human beings with all of their mental prowess are frail indeed when lifted from the surface of the Earth. Pilots require food and rest at regular intervals; are subject to chemical, biological, radiological, and blinding effects; restrict gravitational and altitude limits of aircraft; and are hugely expensive to train and replace if lost. Placing them in an aircraft requires life-support equipment and people to maintain that equipment, and in regard to aerodynamics and radar cross section, has adverse impacts on airframe design. In short, human pilots bring a lot of baggage to aircraft in general, and so *UCAV fighter advantages are a natural reflection of manned-fighter limitations*, with a few added tricks of their own.

Large aircraft with multiple crewmembers and room to move about have nearly limitless range and endurance. This has been demonstrated by B-2s flying halfway around the world and hitting targets, only to fly back to the United States and land at home station. Single-seat fighters have no such luxury but have demonstrated impressive capabilities nonetheless. In Operation El Dorado Canyon fighters flew 14 hours to cover 5,500 miles in the longest tactical mission ever accomplished.[26] Such endurance in fighters is uncommon, and a mission of that length poses risks of fatigue to aircrew, who (tactically speaking) after seven hours en-route to their targets are unlikely to be in peak condition for the attack itself. In his remarks to the American Enterprise Institute in 2005, Gen T. Michael Moseley acknowledged that two reasons to "go down this [UAV] road" were risks to the human and when "the human could be the limit."[27] UCAV fighters offer an endurance limited only by air refueling and perhaps engine oil life. Multiple pilots can manage a single or multiple fighters to and from a theater or target, spending only several hours at a time flying before being relieved. France and Spain denying overflight in Operation El Dorado Canyon tells us, and the 2006 *Quadrennial Defense Review (QDR)* reminds us, that we need to be prepared for antiaccess strategies; UCAV fighters are one way to bring tactical forces to bear at great distances. As the *QDR* states: "Based on the Department's Global Defense Posture Review, the United States will continue to adapt its global posture to promote constructive bilateral relations, mitigate antiaccess threats and offset potential political coercion designed to limit U.S. access to any region."[28]

Human frailty also reveals itself with altitude and G-forces, both of which are within the regular working environment of fighter aircraft. Altitude provides for range/endurance as well as speed. Long-range missiles, such as the advanced medium-range air-to-air missile, perform much better in the less dense air at altitude and maintain higher end-game energy if fired above the speed of sound. For these reasons, F-15Cs can regularly be found operating in the high-30,000- to low-40,000-foot block. Previously exclusive to pilots with full pressure suits, such as in the U-2 and SR-71, F-22 pilots now exceed the 50,000-foot "space equivalent" boundary[29] and employ up to 60,000 feet with the aid of partial pressure suits.[30] Unprotected humans or those experiencing complete loss of cabin pressurization cannot survive at these altitudes; it is here the *human is the limit.* Humans find themselves equally ill equipped to deal with G-forces in excess of about 10Gs over any length of time. Although the body can withstand such force, the heart is simply unable to produce enough pressure to keep oxygen flowing across the membranes of the eye and brain to sustain sight and consciousness. Thrust-vectoring nozzles, increasingly powerful engines, and fly-by-wire flight controls now permit aircraft to perform in radically different fashion than simply rolling and turning. While these innovations are ideal for aerial combat, the human pilot simply can't go where the machinery can; *the human is the limit.*

As a last note on physiological limitations, humans in the cockpit can be blinded by lasers or incapacitated/killed by airborne chemical weapons, biological agents, or nuclear radiation. Fighter pilots train annually to operate in chemical and biological environments, but flying with cumbersome breathing equipment limits performance and often precludes the use of other specialty gear like night vision goggles. Nothing prevents UCAVs from operating in any of these environments; therefore, they must be considered as an instrument in a global environment where access to chemical and biological agents is growing.

Humans are not only a physiological limitation, but they have adverse effects on aircraft design, particularly for stealth. Human pilots require space—space for an ejection seat, space for a control panel, space for life-support equipment, and space to look out and around the aircraft they fly. This space could otherwise be used for fuel or payload, but given that in a UCAV it is likely to be used for avionics and C2 equipment, this point might well be a wash. It is the last requirement for visibility—the canopy itself—that degrades aircraft design. With stealth now an inherent requirement to fighter design (F-117, F-22, F-35), it is critical to limit anything that might increase the radar cross section (RCS) of new aircraft. It is no secret that the largest radar reflectors on any aircraft are flat surfaces; in fighters this includes the radar dish in the nose, the engine intakes/fan blades, and vertical tails, for instance. Numerous aircraft demonstrate efforts to reduce this effect: saw-tooth landing gear panels on the B-2, mesh screens on F-117 engine intakes, engine nacelles on top of the B-2 fuselage where they are unseen by ground radars, and angled vertical tails on the F-18, F-117, F-22, and F-35 (fig. 6).

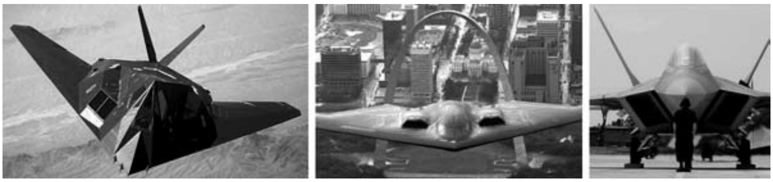

Figure 6. Efforts to reduce RCS: mesh screens, raised nacelles, canted tails. (Photos courtesy of US Air Force.)

Much less considered outside of design circles, however, are the pilot and helmet within the cockpit. A large bubble canopy that gives way to a cluttered cockpit filled with multiple edges can quickly defeat other efforts to make an aircraft stealthy. The F-16 cockpit uses a thin gold film to help diffuse reflected radar energy, as do the saw-tooth edges of the F-117 cockpit. Much simpler in design, of course, is to remove the cockpit altogether and place the engine intake in its place on top of the fuselage (fig. 7). This capability is inherent only to unmanned aircraft as any attempt to minimize the RCS of a cockpit can approach but never equal removing it entirely. Here again, a limitation of a human in the cockpit is an advantage for UCAV aircraft.

Figure 7. Efforts to reduce RCS: gold canopy, saw-tooth edges, raised engine nacelle. (Photos courtesy of US Air Force.)

Another obvious limitation of manned aircraft that gives weight to UCAVs is the vulnerability and penalty of losing aircrew members in combat or as prisoners of war. As long as there have been aircraft, the time and monetary cost of training pilots have been considerable—but much more expensive are the political and strategic implications for losing pilots in combat. In 1960 Francis Gary Powers was shot down over the Soviet Union while performing reconnaissance in his U-2, a mission that the US government denied until it was revealed that the pilot survived and his film had been developed. Relations between the two nations soured, and in May of 1960 the Paris Summit between Pres. Dwight D. Eisenhower and Nikita Khrushchev "collapsed" in what was attributed to Eisenhower's refusal to apologize for the incident.[31] A more recent example of the negative exposure downed pilots create is how Capt Scott O'Grady seized the headlines in June of 1995 when his F-16 was shot down over Bosnia. The US public was enamored with his story, drawing media attention and scrutiny of the military and foreign policy alike. The story repeated itself three years later when an F-117, thought to be nearly invisible to radar, was shot down by a Soviet-made SA-3. Again, stories of the pilot and his rescue circulated in the press and drew unwanted attention to the military and foreign policy (fig. 8).[32]

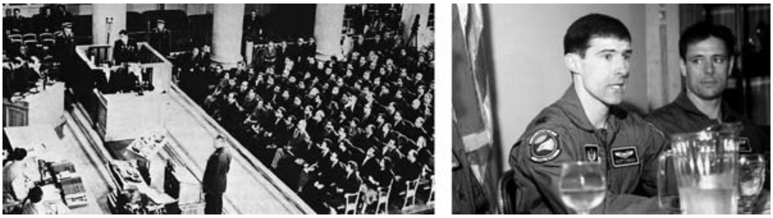

Figure 8. The trial of Gary Powers, Captain O'Grady. (Photos courtesy of US Air Force.)

What wasn't seen in the press in 1995 was the fact that two UAV Predators had been lost within four days of each other. According to a report on the Bosnian conflict released in 2002, one Predator had been lost to engine problems while another was shot down by the Bosnian Serb army.[33] Regardless of cause, these unmanned losses went unnoticed and unquestioned by the media or public at large. The overwhelming success of Desert Storm gave the public the perception that a sanitary war was possible and reinforced the value of human life; it is acceptable to lose machines, not people. General Moseley has acknowledged the benefit of UAVs in high-risk scenarios but was quick to add that we have yet to encounter air defenses we are unwilling to penetrate, even at some risk of lives lost.[34]

While the United States has always been willing to penetrate the air defenses arrayed against us in the past, it's necessary to consider the context of time when proposing the future UCAV fighter. Specifically, the acquisition time for jet fighters is lengthening. As technology advances, it is increasingly difficult to cut off concept development for an ever-evolving weapon system. Coupled with the need to get the most "bang for the buck," it is attractive to package as much new technology as possible into an airframe in an attempt to lengthen its useful life. Chief USAF scientist Dr. Mark J. Lewis has noted how long acquisition periods span multiple changes in political office, making the process of acquisition more difficult and unstable. The bottom line is that each system, once procured, must last as long as possible; new systems are exceedingly difficult and expensive to get off the drawing board and onto the flight line (see fig. 9).

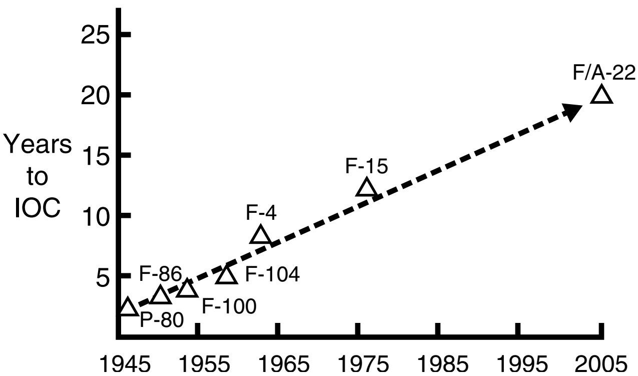

Figure 9. Concept to IOC for Jet Fighters. (Reprinted from Dr. Mark J. Lewis, chief scientist, USAF, briefing [Air Command and Staff College, Maxwell AFB, AL, March 2007].) Compiled from *Post-World War II Fighters* (Washington, DC: USAF, 1986) and data from Secretary of the Air Force Office of Public Affairs. Courtesy of Dr. R. P. Hallion.

Air defense systems of today pose formidable threats to all aircraft, stealth included. Recall that the F-117 shootdown in Bosnia in 1999 was using an SA-3 system fielded in 1961.[35] Systems built *10 years ago*—such as the SA-10, SA-12, and SA-20, exported by the former Soviet Union and built under license in other countries—are much more capable, with ranges nearing 150 nautical miles and altitudes of over 100,000 feet (fig. 10).

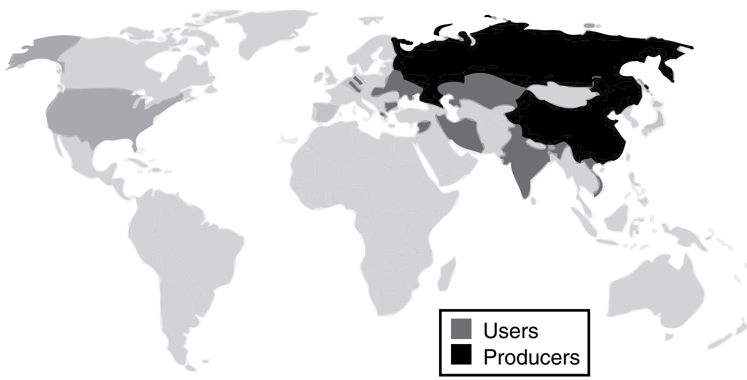

Figure 10. SA-10/12/20 users and producers. (Reprinted from *Wikipedia*, s.v. "Users and Other Versions," http://en.wikipedia.org/wiki/SA-10.)

The F-15 has had to continue in service for over 30 years. If the F-22 and the F-35 are to accomplish the same feat, they must be capable of dealing with new threats that evolve over their life cycle. Although Moore's Law is an analysis of the number of transistors on an integrated circuit relative to cost, it has shown to be a useful tool in forecasting the speed of growth in hard-drive capacity, pixels in digital cameras, and other technology in general. It reveals a logarithmic progression of technology, not a linear one. While it is unclear just what air defenses may look like 20 or 30 years down the road, we can be fairly certain that the F-22 and F-35 will not have changed as drastically. Technology breeds countertechnology to be sure, but as we've found with our legacy aircraft, there are only so many upgrades and patches you can make before it's tactically unwise or economically prohibitive to continue. If we cannot remove the risk or the exposure to that risk, then it is best to reduce the potential consequences of taking that risk. Quite simply, UCAVs remove the element of human risk in future air combat.

A final advantage of a certainly unexhausted list of UCAV benefits is the prospect of controlling multiple fighters with one ground-station pilot (fig. 11). Fighters employ now in twos, fours, eights, or more, and the ability to control multiple UCAVs from one station is a force multiplier. A typical formation today consists of two flight leaders and two wingmen. A minimum of one flight leader must be four-ship qualified and provides tactical direction to the entire formation. Tactics, techniques, and procedures for air combat are well known to all pilots in the formation, but they are virtual extensions of the leader who is responsible for the safety and combat effectiveness of the whole. The transition to controlling multiple fighters with one pilot therefore is no great leap in tactics or concept. As previously discussed, UCAV fighters using dynamic programming are able to maintain formation in cooperative leader-follower relationships. This capability frees up the UCAV operator to control his entire formation through the control of a single unit. As also mentioned, controlling one of four vehicles directly reduces the amount of bandwidth required for relay proportionally.

Figure 11. Raytheon's advanced multiunmanned aerial system's cockpit. (Source: *Defense Update online*, 2006, issue 2, http://www.defense-update.com/products/u/UCS.htm.)

Despite the many and clear advantages to UCAV fighters, some of the risks and limitations have already become evident. In determining if UCAV fighters are the next logical progression for the USAF, it is still necessary to consider these risks, limitations, and costs.

Risks, Limitations, and Costs

As assuredly as this paper has not identified all the advantages and capabilities of UCAV fighters, it is equally impossible to identify all of the risks and limitations that may confront their use in combat. As we have seen thus far, there are at least three major hurdles to overcome if UCAV fighters are to reach their potential: legal issues with autonomy, WVR combat maneuvering, and C2 as a single point of failure.

Throughout this research it has become clear that MITL operations would require substantial bandwidth when operating over the horizon. Video data requires much more bandwidth than audio or simple telemetry. If UCAVs are used in the manner and numbers described, the amount of bandwidth necessary could easily saturate C2 capability. As a minimum, videos that must be streamed to a control station for *each* fighter are radar, targeting pod(s), and synthetic vision (such as DAS). This fact makes autonomous operations like that of the Global Hawk today very appealing but raises the legal issue of responsibility for lethal force. If UCAVs are to interpret and act on data dynamically without MITL, who is responsible when those acts lead to the death of noncombatants or are disproportionate in effect? The law of armed conflict (LOAC) is based on international law arising from the conduct of nations in hostilities over time, as well as treaty law that is binding upon those signatory to it. The laws and customs break down to basic principles that are familiar to those in uniform. Violence may be used only in military necessity, with distinction between civilians and combatants, in a proportional manner to objectives, and with humanity to limit unnecessary suffering.[36]

Based on these principles, *The Military Commander and the Law* (produced by the Judge Advocate General School at Maxwell Air Force Base) gives examples of lawful and unlawful weapons. Among those cited as unlawful are those that kill indiscriminately, to include "weapons incapable of being controlled."[37] It is interesting, then, that the United States did not sign the treaty banning antipersonnel mines. The most common reason offered for not signing the treaty is the important role of land mines in enforcing the demilitarized zone between North and South Korea. The use of these indiscriminate and potentially inhumane weapons is a curious artifact in our foreign policy and gives way to the concept of the ends justifying the means. Other modern weapons that are decidedly indiscriminate are the cruise missile, the JDAM, and BVR missiles. Cruise missiles are used against static targets, however, and typically include planning for time of day, anticipated collateral damage, and so forth. The JDAM also seeks the coordinates programmed into it and is responsible for fratricide in several cases, to include killing three friendly special forces soldiers in December of 2001.[38] The BVR missile works in the same manner, with authority to kill given at launch against targets that have not been seen but have been *identified* by electronic means, point of origin, or other rules of engagement. The shootdown of an Iranian airliner in 1988 by the USS *Vincennes* demonstrated through the death of 248 civilians the serious potential flaws of electronic IFF in beyond-visual-range environments.[39]

If loopholes are not found in existing law, autonomous UCAVs already face these serious challenges. MITL provides for a human to make conscious decisions for applying force as well as someone to hold responsible for mistakes. Autonomous systems must have code, heuristics, DP, algorithms—whatever you choose to call some sort of intelligence—for discriminate killing. Modern sensors can tell an F-15 from a MiG-29. They can tell a T-72 tank from an M1A1 Abrams. They cannot tell a wounded soldier from a healthy one, a chaplain from a combatant, or a terrorist wearing black civilian clothes from a civilian wearing black civilian clothes. While they may be smart enough to attack a tank and not a Coca-Cola truck, they are unlikely smart enough to know if a mob surrounding a tank includes soldiers or liberated civilians. Quite simply, a UCAV is discriminate, but it is not discriminate *enough*—at least *not yet.*

For now, the answer for UCAV fighters seems to require MITL, and MITL will require huge amounts of bandwidth. The present demands for bandwidth have already impacted plans for future spectrum management and hold promise that what is needed may, in fact, be available for the widespread use of UCAV fighters. The March 2007 UAS concept of operations (CONOPS) predicts:

> By 2014 the first UAS possessing networked C2 should be operational. The migration from current point-to-point data links to network data links will allow more users access to high bandwidth data. . . . Future systems that have onboard algorithms to filter and reduce redundant data into processed information can reduce bandwidth requirements and free bandwidth for other systems. Data compression technologies can also reduce the required bandwidth to communicate and pass data. . . . Also, airborne and ground relays (or other UAS acting as relays) can lessen the burden on other BLOS [beyond-line-of-sight] or SATCOM [satellite communications] systems.[40]

The second hurdle for UCAV fighters is WVR combat and the delay found in C2 of the remote vehicle. The command delay is most hazardous inside visual ranges, but it is presumptuous to assume that short-range engagements are a thing of the past. In fact, at least 13 of the kills made in Desert Storm were with short-range missiles in the WVR arena (see table).

Table. Gulf War AIM-9 kills

Date	Target	Pilot	Aircraft	Unit
17 Jan 1991	MiG-21	Fox	F/A-18C	VFA-81
17 Jan 1991	MiG-21	Mongillo	F/A-18C	VFA-81
24 Jan 1991	Mir F.1	Shamrani	F-15C	13 Sqn, RSAF
24 Jan 1991	Mir F.1	Shamrani	F-15C	13 Sqn, RSAF
27 Jan 1991	MiG-23	Denny	F-15C	53rd TFS
27 Jan 1991	MiG-23	Denny	F-15C	53rd TFS
6 Feb 1991	MiG-21	Dietz	F-15C	53rd TFS
6 Feb 1991	MiG-21	Dietz	F-15C	53rd TFS
6 Feb 1991	Su-25	Hehemann	F-15C	53rd TFS
6 Feb 1991	Su-25	Hehemann	F-15C	53rd TFS
7 Feb 1991	Mi-8	Broce & McElraft	F-14A	VF-1
20 Mar 1991	Su-22	Doneski	F-15C	22nd TFS
20 Mar 1991	Su-22	Dietz	F-15C	53rd TFS

Source: "AIM-9 Sidewinder," F-16.net, http://www.f-16.net/f-16_armament_article1.html.

One potential solution for command delay is MITL control until PID of the opposing fighter is made, after which permission can be given for an autonomous engagement. As with firing missiles BVR, "absence of friendly" and PID have both been satisfied, consent to kill has been given by a human (responsibility), and the adverse effects of command delay are overcome with autonomy. If man must remain in the loop for WVR engagements, it will be at a distinct disadvantage given the advanced state of short-range weaponry: thrust-vectoring missiles and helmet-mounted sights, for example. The second potential solution, of course, is complete autonomy, already found to be mutually exclusive with today's LOAC and rules of engagement. Unless the LOAC shifts to permit machines killing discriminately, UCAV fighters will remain tethered electronically to a control station and their human masters.

The final limitation addressed in this research, and perhaps the largest target for our adversaries, is the electronic link required for man-in-the-loop UCAVs. I will quickly dismiss the safety issues of losing link with a remote vehicle, as the QF-4 and Global Hawk have demonstrated the success of lost-link profiles. The fail-safe measure of a return-to-base profile or self-destruct is irrelevant here because the end state is the same; the asset is lost as a combat vehicle until link is reestablished or until the sortie can be regenerated. C2 must be secure and near-continuous with each remote vehicle if MITL UCAVs are to be successful. If flown in cooperative formations, at least one of the fighters in the leader-follower formation will require positive control. Over-the-horizon control in UAVs is now accomplished with SATCOM,[41] and navigation is normally inertial navigation with GPS updates or GPS only. The joint CONOPS for UASs is quick to point out the susceptibility of GPS to jamming and interference. Our command systems will require frequency-agile equipment with transmissions that are secure as well. The *Unmanned Aircraft Systems Roadmap, 2005–2030* cites the most common cause for frequency interference as more often from friendly sources rather than hostile but sums up the critical requirements in one succinct paragraph that calls for all the services to pool resources in an effort to mitigate this threat:

> In general, there are two main areas of concern when considering link security: inadvertent or hostile interference of the uplink and downlink. The forward ("up") link controls the activities of the platform itself and the payload hardware. This command and control link requires a sufficient degree of security to insure that only authorized agents have access to the control mechanisms of the platform. The return ("down") link transmits critical data from the platform payload to the warfighter or analyst on the ground or in the air. System health and status information must also be delivered to the [ground control station] or [unmanned aircraft] operator without compromise.[42]

There is no easy solution to the C2 challenge for ISR UAVs today, let alone the prospects of UCAV fighters in mass replacing their manned equivalents in the future. Prioritized spectrum management will be required among the services, and significant investment will have to be made in the C2 systems necessary to field such a force, from ground stations to satellites to the receiver, and must include some level of redundancy. All of this must be accomplished in a time of increased oversight on military spending, shrinking budgets, and costly new technology.

A great deal has been written about the vast savings available through the use of UAVs, but most research is based on ISR UAVs of similar design and function to the Predator or Global Hawk. Almost nothing is available regarding the costs of UCAV fighters because the concept is so new and, as yet, deemed implausible. The cost of an ISR UAV is very inexpensive indeed, with a Predator costing about $2.7 million and a Global Hawk $19–26.5 million.[43] The hidden expenses are in the fine print, however, where "costs are minus sensor costs." The telemetry package of a QF-4 is roughly $400K alone, but ISR sensor packages can easily exceed the price of the vehicle itself—electro-optical sensors, SAR, and FLIR can reach into the millions.

I will quickly concede that the airframe of a UCAV fighter offers no substantial savings in cost over a manned fighter. *Cost savings* include no cockpit interface (which is significant for design, ergonomics, glass multifunction displays, etc.), no life-support equipment or ejection seat, and no life-support personnel or infrastructure as a minimum. Reciprocal costs *added* include expensive C2 systems (the pilot), C2 infrastructure (life support), and ground control stations (the cockpit) as a minimum. The *real* savings expected in UCAVs come from training and human lives.

Pilots and their aircraft spend a disproportionate amount of time training, and training is an expensive endeavor. A single F-15 sortie, for example, will use roughly 13,000 pounds of fuel in 1.3 hours, or about $4,000 at $2 per gallon of jet fuel. This excludes the infrastructure that supports it, such as the maintenance and inspections required. While the SR-71 is not a fighter by any means, it is useful to note that of its 17,300 sorties flown before retirement, only 3,551 were actual missions, or about 20 percent.[44] Of the roughly 650 hours I personally have in fighters, only 100 hours are in combat, or about 15 percent. Of the 301 F-16 losses prior to the 2005 *Unmanned Aircraft Systems Roadmap* release, only six were lost in combat; 98 percent were lost in training.[45] We do a lot of training indeed, and training is expensive! Training for UAVs can be indistinguishable from flying an actual mission, as it can be done from the same console used for combat aircraft. QF-4 drone pilots at White Sands Missile Range accomplish simulator training on the very consoles they fly the drones with. Whether or not there is a real airplane at the other end of the C2 structure is transparent to the instrumentation before them. This form of training facilitates huge cost savings potential in fuel, parts, maintenance, and aircraft losses. But people, of course, are the greatest savings of all.

Fighter-pilot training in the United States is a road that never ends, but to achieve proficiency as a flight lead takes years of training. Pilot training is a year long, the fighter fundamentals course is several months long, and primary training is about six months long. Before a pilot ever reaches an operational unit, he or she has spent two years in training. It takes about another year to become a flight lead and a short time thereafter to become a four-ship flight lead. It takes even longer to become an instructor or evaluator, and real proficiency comes only after hundreds of hours of training. The loss of a single pilot is so expensive that our military devotes a huge amount of resources and Airmen to recover a pilot who has been shot down. What's more is the time it takes to "grow" a new fighter pilot for one lost in combat. A well-trained pilot force cannot be replaced in weeks or months or a year. The loss of a combat veteran or instructor is even more costly. As General Moseley said, we have yet to find a defense system we can't penetrate, but we may find that the threat systems of tomorrow will narrow the pool of those willing to try.

Conclusion

Department of Defense spending on unmanned systems is spiraling upwards even as military budgets decline. Our senior leaders have seen the utility of UAVs in ISR for their endurance, flexibility, and sheer volume of intelligence. The Air Force has stood up the UAV Battlelab, and Nellis AFB (Nevada) now hosts the Joint UAV Center of Excellence. The age of UAVs is upon us, and as technology advances exponentially, the Air Force must decide what the next fighter will look like. How will we replace the F-22 and F-35 20 or 30 years down the road? There are no technological barriers that prohibit the design and use of UCAV fighters on a large scale. They are capable of cooperative employment, air refueling, WVR and BVR engagement, AI, and CAS. There are anticipated limitations in bandwidth and concern for performance in WVR if MITL is the ultimate solution to command and control, but this can be overcome with automated sequences once permission to engage has been authorized.

The range and endurance of UCAV fighters offer persistence and attractive options in a world of growing anti-access strategies. They offer advantages in performance, altitude, and employment without the limitations of human physiology. UCAV fighters deny the political use of prisoners of war by our adversaries and deny them a great tool in a media campaign. Ultimately, UCAV fighters are not a panacea but offer the presence of force in a threat environment that 20 years from now will be extremely lethal. The costs and risks associated with UCAV fighters are significant but surmountable. The single point of failure may be in our command and control through the RF spectrum for over-the-horizon operations. If sufficient bandwidth can be secured and the control of remote vehicles can be assured, there are immense dollar costs to be saved in their employment. While we cannot place a price on the human element, the value of our pilots is demonstrated in the training they receive and the assets assigned to recover them. In the context of future threat systems and antiaccess strategies, the Air Force would be foolish not to pursue UCAV fighter technology.

> *Victory smiles upon those who anticipate the change in the character of war, not upon those who wait to adapt themselves after the changes occur.*
>
> —Giulio Douhet
> *The Command of the Air*

Notes

(All notes appear in shortened form. For full details, see the appropriate entry in the bibliography.)

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38. Gruetzmacher, Holtery, and Putney, *Fratricide.*

39. International Civil Aviation Organization, *Resolution and Report.*

40. *Joint Concept of Operations for Unmanned Aircraft Systems,* 96.

41. Global Hawk Integrated Communications System, "L-3 Communications."

42. DOD, *Unmanned Aircraft Systems Roadmap*, 68.

43. Ibid., 56.

44. *Wikipedia*, s.v. "SR-71 Blackbird."

45. DOD, *Unmanned Aircraft Systems Roadmap*, 70.

Abbreviations

ACSC	Air Command and Staff College
AI	air interdiction
AIM	air intercept missile
BVR	beyond visual range
BFM	basic fighter maneuvers
C2	command and control
CAF	combat air forces
CAS	close air support
CONOPS	concept of operations
DAS	distributed aperture system
DP	dynamic programming
FLIR	forward-looking infrared
GPS	global positioning system
ID	identification
IFF	identification, friend or foe
IR	infrared
ISR	intelligence, surveillance, and reconnaissance
JDAM	Joint Direct Attack Munition
JSF	Joint Strike Fighter
Ku	Kurtz-under band
LOAC	law of armed conflict
MHz	megahertz
MITL	man-in-the-loop
PID	positive ID
QDR	*Quadrennial Defense Review*
RCS	radar cross section
RF	radio frequency
SAR	synthetic aperture radar
SATCOM	satellite communications
TACAN	tactical air navigation
UA	unmanned aircraft
UAS	unmanned aerial system
UAV	unmanned aerial vehicle
UCAV	unmanned combat air vehicle
WEZ	weapon engagement zone
WVR	within visual range

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