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Unmanned Combat Air Vehicles

What men do in aircraft and why machines can do it better.

> *"An effective UCAV will be enabled in the next century as the result of the simultaneous optimization of information flow, aircraft performance, and mission effectiveness. The UCAV will not completely replace the inhabited aircraft for decades, if ever, but the presence, or absence, of a pilot is now a design trade that can be made in a logical way."*[1]

Commercial airplanes on autopilot take off, fly to a distant destination, and land; autonomous cruise missiles pound targets over a thousand kilometers from their launch point; unmanned space missions orbit satellites and explore other planets, and yet the armed forces continue to buy aircraft that require an onboard pilot to guide them into enemy territory and carry out well-defined missions. On the other hand, the pilots and operational specialists who run those missions cannot begin to fathom an unmanned vehicle capable of the level of reliability and versatility that current manned systems enjoy. In their view, no suite of sensors and no array of computers or offboard guidance can substitute for a trained man with two eyes in the cockpit. However, defense institutions have recently begun to reject the latter philosophy in favor of the former. Today's fighter planes are scheduled for retirement in massive numbers starting in 2015.[2] Potential replacements include the F-22 for air superiority and the Joint Strike Fighter for interdiction and close air support. But this year the U.S. Air Force and Defense Advanced Research Projects Agency (DARPA) also began a preliminary Unmanned Combat Air Vehicle (UCAV) Advanced Technology Demonstration (ATD) program. Lockheed Martin, Boeing, Northrup Grumman, and Raytheon Systems won contracts as part of this ATD, and are making substantial investments of their own to develop UCAV concepts. If the program is carried through, the U.S. could have an operational fleet of UCAVs as early as 2010.

Of course, skeptics remain, and such ambitious programs invariably encounter difficulties in development. Nevertheless, I will show not only that the technology exists to develop UCAVs, but also that UCAVs will be substantially more cost-effective than current weapons systems.

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[1] New World Vistas: Summary, p.34

[2] "Autonomous Attacker," *Flight International*, 20-May-98 p.30

Cost-effectiveness. The effectiveness of a system is tied not only to its combat effectiveness (i.e., ability to destroy targets), but also to such factors as theater integration effectiveness and costs of acquisition and operation. Expensive acquisitions programs are shut down during budget cuts, operationally expensive weapons aren't maintained at full readiness, and weapons that aren't used in training usually aren't trusted by battlefield commanders during wartime. Regardless of their capability, expensive, complex systems are often discarded in favor of cheap, simple systems that can get the job done more reliably.[3]

System costs are also of great concern. Since the Gulf War, commanders have demonstrated a clear preference for using million-dollar cruise missiles instead of manned aircraft to carry out strategic attacks. After all, captured or killed aircrews are extremely costly, both in terms of public relations and morale, and in terms of dollar-replacement value (it costs millions of dollars to train and maintain pilots). Cruise missiles, then, have demonstrated just how expensive it is to use manned combat air vehicles.

UCAV systems can provide all of the capability of manned systems with total costs below those of cruise missiles. While the vehicle acquisition cost will be a fraction that of manned vehicles, the most significant savings with UCAVs are expected to accrue from how they are used in training and operations. I will begin the analysis of UCAV cost-effectiveness by showing how proposed UCAV systems compare to current systems on cost. Then I will provide a survey of current technology to show just how realistic UCAV proposals are. I will touch on the airframe, engines, flight control, payload, communications, and targeting technologies. I will also look at the issue of survivability and the use of UCAVs in training and operations. Finally, I will survey the state-of-the-art in UAV (Unmanned Air Vehicle) systems, and show where UCAV systems will take us. In a sense, this entire paper is about cost-effectiveness, since it shows how unmanned vehicles can be both cheaper and better.

Precision interdiction mission. Ground-attack sorties used to be carried out by small fighters with dumb bombs. Later, stealth bombers with precision-guided bombs took over the role. Today the most popular interdiction vehicle is the cruise missile. Presumably, the predilection of

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[3] Kross, p.11. Kross gives numerous excellent examples of expensive systems with impressive specifications that were not as reliable or cost-effective as simpler, cheaper systems.

commanders for cruise missiles is an indication that once all cost, risk, and effectiveness factors are taken into account, cruise missiles are the most cost-effective interdiction vector.

The most popular specification for UCAVs is a vehicle that costs under $15 million and can deliver two 1000lb munitions with the same reliability as two cruise missiles (which have a 1000lb payload).[4] To evaluate the cost-effectiveness of UCAVs, we can compare them to cruise missiles at various levels of attrition. The current acquisition price of cruise missiles is as low as $750,000. Assume the worst-case UCAV price of $15 million. Also assume that the cost of a UCAV sortie is about $10,000 in fuel and maintenance (this is par for manned aircraft) plus $90,000 in munitions, operations, and sortie costs.[5] Thus, UCAVs incur a $100,000 charge per sortie where cruise missiles effectively cost $0. Assume that UCAVs and cruise missiles suffer the same attrition rate, *a*%, and are equally effective at striking targets.[6] Therefore, a UCAV is expected to fly $s = \frac{100}{a}$ sorties at a cost per target of $\frac{1}{2}\left(\frac{\$15\text{MM}}{s} + \$100\text{k}\right)$. Comparing this to the cruise missile cost of $750k per target, we see that even with our somewhat antagonistic assumptions, UCAVs would be cheaper up to an attrition rate of 5%.[7]

Air-superiority mission. There is no clear unmanned alternative to a UCAV that can foray into enemy territory and evade enemy air defenses while shooting down enemy aircraft. One reasonable cost-benefit analysis would be to suggest that as along as the UCAV destroys no less than its own value in military hardware, it is cost-effective. This is easy, since UCAVs are supposed to cost less than one-third of a manned aircraft, meaning an advanced enemy could shoot down 3 UCAVs for every manned fighter it loses and we would still break even. This ignores the benefits of keeping expensive American pilots out of danger, but also the possibility that next-generation manned air-superiority fighters could maintain disproportionately low

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[4] *Aviation Week & Space Technology (AW&ST)*, 29-Jun-98, p.21

[5] This figure was picked in part to give a round number. Dumb munitions cost under $5000 apiece and, as will be seen, it is expected that UCAVs will deliver dumber rather than smarter munitions because they have no standoff requirement. UCAVs would incur operations and support costs that cruise missiles wouldn't because the vehicles are more expensive to transport, and require handling to launch and recover. They may also require command center personnel to supervise the sortie, and additional sortie support like aerial refueling.

[6] Even though cruise missiles are smaller than UCAVs, they have no countermeasures and are relatively dumb. At the same time, however, they don't have to fly a return leg and land like UCAVs. It is reasonable to assume that these factors would balance out their survivability. However, we are being generous here in assuming that cruise missiles would be as effective as UCAVs—there are ground targets, such as those that lie in deep valleys, that cannot be effectively attacked by current cruise missiles but that could be by our UCAV concept.

[7] Certainly, their cost would decline if they were used in large quantities, just as the cost of cruise missiles is now almost half of what they originally cost.

attrition rates, rendering air-superiority UCAVs cost-*in*effective in comparison. However, as will be explained in the *Survivability* section, it seems unlikely that manned aircraft could keep attrition rates below UCAVs on the same air-superiority missions.

Technology. UCAVs can be approached both as *unmanned fighters* and as *glorified cruise missiles*. While the most popular design incarnations of UCAVs resemble state-of-the-art strike fighters with the cockpit removed, UCAVs are also being considered that are more like $2 million reusable cruise missiles, as in the Lockheed Martin concept shown here.

Up to 40% of the weight and volume of a manned fighter is dedicated to the human interface and life-support systems.[8] By removing the canopy, ejection seat, oxygen and pressurization system, G-suit system, displays and controls, as well as the redundancy and fault tolerance demanded of manned systems, DARPA expects to be able to cut the dry weight of a vehicle capable of a 2000lb weapons payload to as little as 8000lb. Engineers hope that the small size of such a vehicle might allow for non-hydraulic, all-electric actuators.[9] Replacing hydraulic tubing and pumps with electric cables would not only save more weight, but also prove more reliable.

Both stealth and aerodynamics would be enhanced by removing the canopy and vertical stabilizers prevalent on manned airframes. The prospects of a low all-aspect radar cross section may be what motivated DARPA to select contractors with known stealth experience for the UCAV ATD. All design drawings have shown attention to stealth details, like sawtooth joints and edges, and angled faces. Northrup Grumman released airframe designs of a gull-winged, tailless UCAV shown here. The airframe measures 27ft long with a 24ft wingspan and 6ft height—with gear down.[10]

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[8] "Unmanned Strike Next for Military," *AW&ST*, 2-Jun-97, p.46

[9] Dr. David Whelan, Director of DARPA's Tactical Technology Office, explained (personal Email) that the problem up to now has been in getting enough torque with electric actuators to maneuver an aircraft. If UCAVs are significantly smaller aircraft, this may not be a problem.

[10] "Gull-Wing UCAV Eyed For U.S. Aircraft Carriers," *AW&ST*, 16-Jun-97, p.56

The maneuverability of UCAVs could vastly exceed that of manned aircraft. Even with G suits to keep blood from pooling in the lower extremities, human beings pass out if subject to maneuvers harder than –3G or +10G. Humans are also quickly exhausted by continuous heavy maneuvering. By removing men from the vehicles, the next constraint appears to be the engine—centrifugal forces cause normal turbines to go out of round and fail above 20G.[11] Nevertheless, the airframes and mechanical components can readily be designed to operate out to the +/-20G envelope. Also, unmanned systems can more readily take advantage of inverted flight. By designing all essential non-stealthy features—engine inlet and exhaust, landing gear and weapons bay doors—onto one side of the vehicle, it can roll over after takeoff to shield them from ground view during flight.

The range, speed, and loiter capability of UCAVs are also increased over manned aircraft by their improved aerodynamics and reduced weight. According to *Aviation Week*, "In-flight refueling of unmanned aircraft is not considered a difficult task...."[12] And unlike current manned fighters, which are restricted from long sorties because they cannot carry a replacement pilot,[13] refuelable UCAVs could fly indefinitely. Hypersonic UCAVs are contemplated since, in addition to their higher thrust-weight ratio and reduced aerodynamic drag, they are not constrained by the pressurization and temperature shielding required to accommodate human beings. The Navy is examining vertical-attitude take-off UCAVs in addition to conventional vertical take-off and landing designs to facilitate ship-based launch and recovery.

Flight Control & Navigation. Last year, the NASA X-36 program successfully flew two unmanned, tailless drones, demonstrating the ability of computerized flight control systems to perform aggressive maneuvers in unstable airframes. The new flight control systems even compensate for simulated damage. "Normally, when you have a major control effector fail,

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[11] "Payload, Not Airframe, Drives UCAV Research," *AW&ST*, 2-Jun-97, p.51

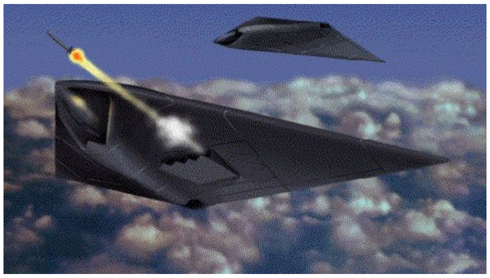
[12] *AW&ST*, 2-Jun-97, p.51

[13] Even during wartime, pilots are required to get a certain number of hours (usually 8 or 10) of "crew rest" before a mission. To fly longer than 12 hours, they are given amphetamines, as was supposedly the case in the 18-hour mission to bomb Libya. However, even drugs can only prolong human functioning for so long.

you'd be in a come-home state. But we always had a fighting aircraft. The performance and controllability were good enough that you'd be willing to stay and fight, even in a failure state."[14]

Navigation is critical to the ability of UCAVs to operate remotely and autonomously. State-of-the-art navigation systems provide phenomenal capabilities in this respect. Most combine the Global Positioning System (GPS) with Inertial Navigation Systems (INS—usually ring laser or fiber-optic gyros). For example, one modern GPS/INS module weighs under 20lbs and provides positional accuracy of at least 16m CEP[15] and velocity to within 0.03m/s RMS (Root Mean Square). Because GPS is expected to be jammed by enemy defenses, such navigation devices function even with intermittent losses of GPS signals.[16]

Terrain-Referenced Navigation (TRN) offers further refinements to navigation. Databases exist containing 100m-resolution Level 1 Digital Terrain Elevation Data for all land areas. Onboard TRN systems can be loaded with this data and thereby provide positional accuracy of 30m CEP and velocity to within 4m/s RMS (although this requires flight under 1500m altitude using a radar altimeter at least 75% of the time). By extrapolating the vehicle's vector, this system even renders optimal nap-of-the-earth flight paths that can be followed autonomously.



Payload. In order to preserve stealth and aerodynamics, UCAVs will carry all weapons internally, as will the F-22 and Joint Strike Fighter. One of the great advantages of UCAVs is their ability to use dumb weapons. The cost and weight of weapons are substantially reduced by putting all the sensors, guidance, and propulsion technology on the survivable, reusable UCAV instead of on the ordnance to be exploded. By getting in close to fixed targets with dumb weapons (something large, manned aircraft are less comfortable doing) UCAVs can strike with the same precision as advanced guided munitions. In contrast, manned vehicles are moving towards expensive stand-off weapons that are practically UCAVs in themselves.

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[14] Gary Jennings, Boeing X-36 program manager, as quoted in *AW&ST*, 2-Mar-98, p.58

[15] Circular Error Probable—indicates 50% probability of any error falling within a circle of the given radius about the true value.

[16] "Honing Airborne Navigation," *Jane's International Defense Review*, 1-May-98, p.32

The 2000lb payload designated by DARPA would accommodate two standard Joint Direct Attack Munitions, eight small smart bombs (which use internal guidance to home on targets), or even Locass guided antiarmor submunitions. Another DARPA program, the Miniaturized Munitions Technology Demonstration, aims to develop advanced explosives and penetrators that give 250lb munitions the same effect against hardened targets as conventional 2000lb-class bombs like the MK-84.[17]

Communications. "Robust, jam-proof communications is the critical issue," said Larry Birckelbaw, program manager for the DARPA UCAV program.[18] One of the great prospects for UCAV operations is the ability to form a distributed network in the sky that coordinates diverse sensors and weapons in real-time. Although they will function autonomously, some amount of operator input and supervision will always be required for UCAVs. At a minimum, UCAVs will have to receive data on threats, flight path and waypoints, and target locations and type. Weapons release will require confirmation by a human operator, and UCAVs will have to carry a reliable self-destruct mechanism not only to prevent collateral damage should they go out of control, but also to safeguard sensitive technology and the theater data they carry onboard. They will also have to receive and respond to queries for location and status. UCAVs might also broadcast intelligence on popup targets as they are encountered.

All of this requires substantial communications bandwidth—"the most precious commodity on the battlefield," according to Birckelbaw. Fortunately, technology is stepping up to the problem. Civilian communications satellite constellations can be used for theater-wide broadcasts of information. The military has its own specialized constellations in place for this purpose, like MILSTAR: "The MILSTAR constellation or its follow-on could serve as the primary C^2 communications network for [UCAV] platforms. MILSTAR's narrow-beam antennas coupled with broad-band frequency hopping provides isolation from jammers and a very low probability of detection."[19]

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[17] Carmichael et al, Ch.5

[18] "Aircraft, UCAVs: An Uneasy Mix," *AW&ST*, 3-Aug-98, p.67

[19] Adm James B. Busey IV, "MILSTAR Offers Tactical Information Dominance," *Signal*, 11-Jul-94, as quoted in Carmichael et al, Ch.5.

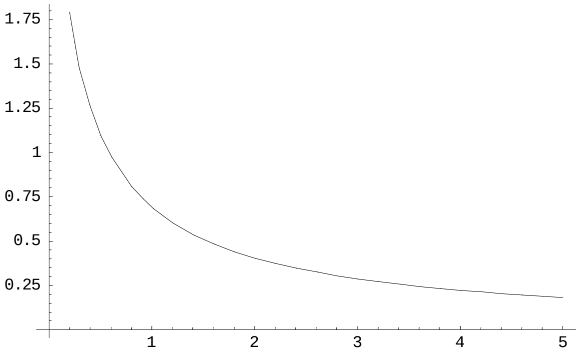

Figure 1. Graph shows the decrease in communications capacity with jamming by plotting capacity against the ratio of jam to broadcast power at the receiver.

Broad-band frequency hopping and microburst communication substantially reduce susceptibility to jamming. The information capacity of a channel is proportional to broadcast power divided by jamming power, as shown in *Figure 1*. For a band of width *W*, the communications capacity is $C = W \log\left(1 + \frac{B}{JW}\right)$ bits per second, where *B* is the broadcast power and *J* is the jamming power.[20] Therefore, as the broadcaster expands the frequency band in use, the jammer must consume proportionally more power to limit the capacity of his communications. With microburst communications, the jammers cannot tell what channels are in use to begin jamming before a message has been sent. Thus, technology tends to favor the broadcaster rather than the jammer. Furthermore, homing anti-radiation missiles (HARM) that lock onto jamming radiation sources are widely deployed. Just the presence of these in a theater can discourage high-power jammers from operating even momentarily, since modern HARMs can stay locked on targets even after they stop radiating.

If a UCAV loses communication contact, it would have to be programmed to loiter or turn for home until a signal is reacquired. However, the number of communications paths available in a theater should provide UCAVs with ample recourse even in hostile environments. In addition to broad-band radio communications from satellites and friendly bases and aircraft (including forward reconnaissance UAVs doubling as communications relays), laser and other all-weather line-of-sight communications are possible that are practically unjammable. For example, a communications craft at an altitude of 15km can maintain a line of sight with attack craft, flying at altitudes of just 1km, up to ranges of over 400km.[21] On the other side, communications at certain frequencies are absorbed by the atmosphere, permitting covert, practically unjammable communication between teamed UCAVs, or UCAVs and nearby motherships.[22]

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[20] Cover & Thomas, *Elements of Information Theory*, John Wiley & Sons, 1991.
[21] New World Vistas: Summary, p.28
[22] For example, broadcasts around 60GHz are absorbed by the atmosphere over just a few kilometers (*AW&ST*, 3-Aug-98 p.67).

Targeting. State-of-the-art sensors will allow targets throughout a theater to be identified and relayed through C³I (Command, Control, Communications & Intelligence) networks in near real-time. In addition to the time-tested AWACS (Airborne Warning and Control System) for long-range detection of airborne threats, the military has deployed a JSTARS (Joint Surveillance Target Attack Radar System) for stand-off detection of ground targets. The capabilities of the moving-target radar on this airborne system are phenomenal: It can scan a ground area of more than 27,000 square kilometers every minute, detecting moving targets with speeds as low as 4 knots (perhaps slower) to within 10 meters of their true position.[23] It is also equipped with a synthetic aperture radar which produces detailed images of small ground areas. UAVs are being prototyped that have similar capabilities, like the Global Hawk, which can travel to a theater 5000km away and loiter for 24 hours at altitudes up to 20km.[24]

DARPA is also preparing to deploy a 24-satellite “Starlite” constellation by 2005.[25] These satellites will perform high-gain electronic support measures (detection, location, and identification of electromagnetic radiation) through radar antennas, and will also be equipped with synthetic aperture radar for imaging of ground target areas.[26] These data can be directly integrated to pick out targets and assign them to UCAVs. Of course, the UCAVs will carry their own sensors capable of detecting popup threats. But the real power of these next-generation systems is the ability of massively capable off-board sensors to provide information needed by the quiet and simple UCAVs.

Survivability. The most significant factor in determining the cost-effectiveness of a UCAV system is its survivability. Aircraft that venture into enemy airspace encounter formidable air defenses consisting of radar-guided anti-aircraft artillery, surface-to-air missiles, and fighter-plane interceptors. The ability to cope effectively with these threats will largely determine the attrition rate of UCAVs, which will in turn affect their attractiveness in comparison to throwaway cruise missiles and manned fighters. It appears that UCAVs are particularly competitive in this respect.

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[23] CBO, p.57

[24] CBO, p.61

[25] Army Information Paper. Available at: http://huachuca-dcd.army.mil/tencap/equipment-Info/starlite.html

[26] Dr. David Whelan. Presentation at the Unmanned Combat Air Vehicle Industry Day Meeting – Joint DARPA / Air Force Program, February 23, 1998.

Because they are reusable, UCAVs can afford to carry more onboard sensors and intelligence to deal with threats than can cruise missiles. Also, because they are more stealthy and maneuverable, UCAVs are potentially more survivable than manned air vehicles. UCAVs will depend on offboard real-time intelligence to alert them to known threats so that they can take appropriate countermeasures. They will also carry their own sensors for the enemy radar used to detect them and guide weapons. They may even be equipped with their own short-range radar to precisely track incoming threats like missiles and aircraft (again, relying on wavelengths that are absorbed quickly by the atmosphere in order to avoid giving away their own existence to enemy sensors) and take end-game evasive action.

Countermeasures available to UCAVs include signature reduction, jammers, deceivers, expendables, and tactics. Radar and infrared signatures are of primary concern. Acoustic and electromagnetic signatures are also giveaways, but the former is not of much use against a high-subsonic or supersonic vehicle, and the latter is suppressed as much as possible through radio silence.

Radar. The radar signature of an aircraft is summed up in its Radar Cross Section (RCS, denoted by σ). Range and σ are the only two factors that can be controlled to reduce susceptibility to detection by radar. A radar with power *P* and antenna gain *G* will have a power density of $\frac{P_r G_r}{4\pi R^2}$ at range *R*. The power of the echo returned by the aircraft is $\frac{\sigma P_r A_e^2}{4\pi \lambda^2 R^4}$ (where A_e is the receiving area of the antenna) meaning that the lower its RCS and the greater its range from a radar, the harder it is to detect.[27] While σ varies with the direction from which an aircraft is viewed, it can be substantially reduced overall by changing the reflection and absorption properties of the skin of the airframe. The shape of the airplane can be modified to reflect incoming rays away from their source, and some enhancements to the skin increase internal absorption of radiation. Another stealth tactic is to increase the impedance of the skin by applying a voltage to it.[28]

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[27] Ball, p.378. $G_r = \frac{4\pi A_e}{\lambda^2}$ and λ is radar wavelength (usually between 1m and 1mm). (There are 4π steradians in a sphere.)

[28] Ball, p.233, 290

Jamming can be used to mask a plane's RCS. By broadcasting noise across the frequencies an enemy radar scans, it is unable to pick out the relatively faint echo of the aircraft itself. In general, this requires substantial power and so the mission is carried out by dedicated jamming aircraft in a sortie. However, not only are dedicated jammers susceptible to HARMs, but also their position can be triangulated by two disjoint radar antennas.[29]

More effective than blind jamming is deception, or spoofing. Some examples of spoofing techniques that use relatively low power include "range-gate pull-off" and "inverse con-scan" (for conical scan tracking radars). To execute a range-gate pull-off, the spoofing transmitter gradually amplifies the radar signal returned by an aircraft. Once it is sufficiently high to have captured the radar's gain control, it is slowly delayed, making the apparent range increase. Finally, with the radar focussed far away from the real aircraft, it can be shut off. Inverse con-scan is used against radars that track a target by looking side to side in order to maximize their signal. As they scan to one side, the spoofing transmitter boosts the signal, making the tracker continue off to that side and lose lock.[30]

Expendables can also be used to stimulate and distract enemy radars. These include towed and miniature air-launched decoys that mimic the RCS of real aircraft. Chaff—electric dipoles cut to precise lengths and dispensed into the turbulent air behind a plane—can simulate a target for a given wavelength of radar.[31] Also, low-level flight can make radar tracking almost impossible because of both the ground clutter and the effects of multiple reflections from the ground.

Infrared. The infrared signature of an aircraft is much more difficult to suppress—the total heat radiated by an aircraft at a given speed and engine power is pretty much fixed.[32] Attempts are always made in design to minimize the temperature generated by engines, aerodynamic

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[29] Nevertheless, Ball notes, "All forms of noise jamming are generally most effective if several jammers are scattered geographically and used simultaneously. With several jammers in different directions, the PPI (plane position indicator) picture can be so confusing that the radar operator has difficulty determining the direction to any one of the jammers" (p.282). However, as computerized signal analysis matures, it will become more difficult to deceive radars in this manner.

[30] Ball, p.282

[31] The dipoles must be cut to ½ the wavelength of the radar being decoyed, and $\sigma/.16\lambda^2$ dipoles must be dispensed to mimic an RCS of σ to a radar of wavelength λ. Ball, p.299.

[32] It is proportional to temperature to the *fourth* power. Ball, p.238.

heating at high speeds, and the reflectivity and emissivity of the air frame. Yet it is difficult to counter weapons that track an infrared signature because they can do so passively.

IR countermeasures include flares, towed decoys, lasers, and deceivers. Unfortunately, flares are not effective against modern heat-seeking missiles because they can't truly match the spectrum, brightness, or size of a real vehicle. Frequency modulated infrared deceivers could confuse mechanically scanned seekers, but won't work against newer missiles with entirely electronic seekers. Fortunately, there are other options. Northrup Grumman, for example, has tested production missile warning systems[33] that track the ultraviolet emissions of a missile's solid propellant exhaust with sufficient accuracy to aim an infrared laser at the seeker, effectively blinding infrared missiles. Such countermeasures could be installed in UCAVs.

Evasion. Evasive maneuvers can be used against both missiles and manned fighters at close ranges. Even with simple evasion algorithms, UCAVs should be able to evade more effectively than manned air vehicles, primarily because they can pull more than twice as many Gs in any direction.

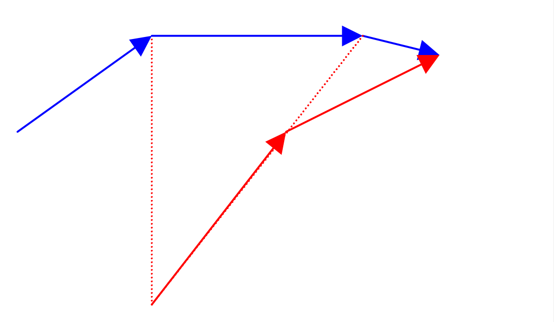

Figure 2a. A successful lead pursuit by missile (red) of UCAV (blue), resulting in a hit at t_3.

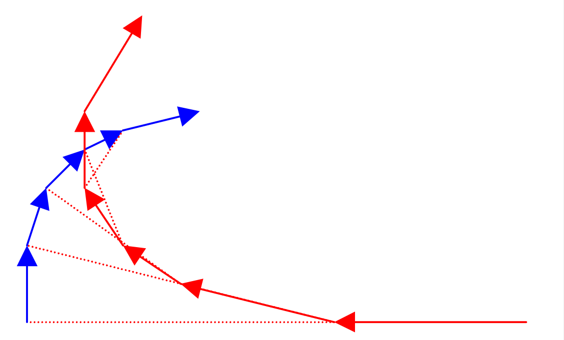

Figure 2b. Here the UCAV evades a missile flying direct pursuit by maintaining an orthogonal vector. Notice that by t_4 the missile is no longer able to pull hard enough to continue pursuit.

Missiles either fly in direct pursuit of a target, or else try to follow a straight-line, "lead" collision course to intercept a target following a fixed trajectory (as shown in *Figure 2a*).[34] A simple evasion strategy can thwart both threats. Beginning a few seconds before impact, a UCAV should perform a rolling, high-G turn to keep it orthogonal to the vector of the threat. By rolling, a UCAV prevents a lead-angle intercept since it can turn anywhere within the plane orthogonal to the missile's vector. Thus, all missiles are forced to fly pursuit trajectories. A successful evasion by this strategy of a missile flying direct pursuit is shown in

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[33] E.g., the AAR-54. See "DIRCM (Directed Infrared Countermeasures)," *AW&ST*, 26-Oct-98, p.44.

[34] Ball, p.107

Figure 2b. (The UCAV can also roll in such a way as to maximize the use of gravity to sustain its own speed, which is quickly consumed by aerodynamic forces in high-G maneuvers.)

For airplanes, the turning rate produced by an acceleration G at a velocity v is given by the acceleration vector orthogonal to its velocity. Assuming the engine produces enough thrust to maintain a constant speed, we have $\frac{dv}{dt} = v\frac{d\theta}{dt}$, therefore the turning rate $\frac{d\theta}{dt} = {}^{G}\!/_{v}$. *Figure 3* shows the turning rate in degrees per second produced by a 20G turn (i.e., an orthogonal acceleration of about 200m/s²) at various speeds. Note that even at Mach 1 (usually around 350m/s) such a vehicle can make a 90° turn in under 3 seconds, orienting itself perpendicularly to a threat from any direction.

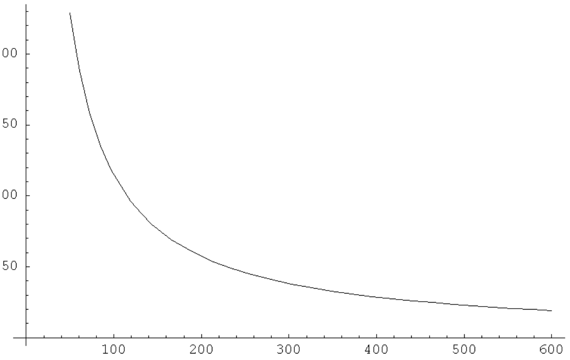

Figure 3. Turning rate in degrees per second versus speed in meters per second at 20Gs.

We should wonder if UCAVs capable of 20Gs can outmaneuver missiles. This can be calculated by considering the case of a breakeven missile intercept—one in which the vehicle maintains a vector orthogonal to the missile and the missile is just able to keep up. In such a case, we would have the turning rates equal—i.e., $d\theta_m = d\theta_u$ or ${}^{G_m}\!/_{v_m} = {}^{G_u}\!/_{v_u}$. In other words, a missile going 3 times the speed of a UCAV has to pull at least 3 times as many Gs to intercept it. This analysis does ignore the "endgame," where the minimum turning rate of the missile needed to follow the target is dominated not by the turning rate of the target, but by its orthogonal velocity component. This occurs at very close ranges to the vehicle—potentially within lethal range. A missile designer thus faces several tradeoffs. He can increase the quantity of explosives in the warhead in order to increase its lethal range, but does so at the expense of maneuverability. Also, he can increase the turning rate by reducing the speed of a missile, but if he does too much the missile may never overtake its target. These are complicated tradeoffs and won't be further analyzed here. We will simply point out that when a missile's turning capacity exceeds the breakeven threshold, it can almost surely intercept the vehicle; if it falls short of that threshold, the vehicle can almost surely evade even if the missile maintains lock.

In reality, a factor of 3 speed over the target is appropriate for most anti-air missiles. According to one source, "Anti-aircraft missiles are usually designed with a factor of three margin in lateral acceleration over that of the target aircraft, although a few missiles have acceleration capability as high as 80G."[35] As currently envisioned, UCAVs that can't break the lock of a lethal, 80G missile would probably succumb to it. (Note that by the same analysis, manned aircraft can't expect to survive locked missiles of even 30Gs.) However, the addition of the numerous countermeasures already considered may balance the equation substantially in favor of the UCAVs. On the other hand, hypersonic UCAVs, if developed, could probably outrun any threat.

Other factors. Two final tactics for increasing UCAV survivability are low-level and nighttime flying. Facilitated by TRN, UCAVs have no trouble flying nap-of-the-earth paths. At such low altitudes, they are not only hard to detect, but almost impossible to engage with ground-based weapons. Also, UCAVs suffer no performance penalty for flying at night. Night flying proved invaluable to survivability in the Gulf war, where F-117, F-16, F-111, and A-10 aircraft returned damage-free from every night sortie.[36]

Operations & Training. War fighters dominate their enemies by gaining an advantage in the observation, orientation, decision, action (OODA) loop.[37] Even in the Gulf War, theater OODA loops were on the scale of days—limited by the time required to collect intelligence, select and approve targets, and schedule offensive sorties. The ability of lethal UCAVs to loiter for extended periods and function within real-time C^3I networks poses the possibility of OODA loops on the order of seconds.

As has been shown, UCAVs can perform not only high-risk missions, but probably even standard manned missions at a fraction of the cost of manned systems. The use of remote operators for UCAV systems yields many benefits. Some proposals would put operators on manned C^2 aircraft in the theater. For example, an F-15E Weapons Systems Operator could direct a strike package of perhaps a dozen UCAVs while the pilot uses the F-15's radar to illuminate targets from a distance.[38] In concepts like this, UCAVs become more like offboard smart weapons than an unmanned strike force. More popular, however, is the concept of a

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[35] New World Vistas: Summary, p.35
[36] GAO, p.21
[37] Carmichael et al., Ch.3
[38] "Who Needs Stealth?," *AW&ST*, 21-Sep-98, p.25

UCAV command center far from the forward edge of the battle area. In this scenario, well rested specialists with powerful equipment receive battlefield intelligence and direct UCAVs in enemy territory through the communications web. The vehicles themselves are expected to be capable of sustained rates of three sorties per day, with a surge rate of five sorties per day. They can be flown directly into the theater or supplied by C-5 and C-17 transports.

Peacetime savings. UCAVs can win the greatest savings over manned vehicles during peacetime. Support costs over the life of a manned aircraft can be equal to its acquisition cost.[39] Just getting a fighter off the ground for a training sortie can run into 5-figures per plane and generate on the order of 30 maintenance man-hours of work.[40] Since simulators can train UCAV operators at least as well as the real thing (and at a much lower cost), UCAVs would practically never have to be flown in peacetime. (The vehicles themselves can be treated like a "wooden round," and kept with minimal maintenance in flyable storage.) This is expected to result in a total operational savings (both in sortie costs and in the associate personnel and logistics chains) of 80% over manned systems.[41]

Peacetime attrition is also a critical cost consideration. Current manned fighters have an expected lifetime (before accidental destruction) of 40,000 flying hours. Current UAVs last only 500 hours.[42] While this rate for unmanned vehicles will almost surely improve as the technology matures, even such a poor rate would be cost-effective if they never flew except in battle.

Current UCAVs. The closest thing the U.S. has to a UCAV right now is the widely successful Tomahawk cruise missile. However, the Israeli Defense Force has deployed a small, reusable UCAV called CUTLASS and claims to have used it in combat. Developed by Raytheon and Israel Aircraft Industries, this 275lb propeller plane has a 300km range and carries a 35lb fragmenting warhead to destroy missile launchers and radars. CUTLASS follows operator-designated waypoints to a search area where it autonomously searches for potential targets and queries the operator for weapons approval. Built from existing technology, the system costs only $160,000 per copy.[43]

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[39] "High-G Flying Wings Seen For Unmanned Combat," *AW&ST*, 11-Nov-96, p.58

[40] Kross, p.60

[41] "Unmanned Strike Next for Military," *AW&ST*, 2-Jun-97, p.47

[42] *Flight International*, 20-May-98, p.30

[43] "USA considers strike UAV for early service," *Jane's Defence Weekly*, 23-Sep-98

Plenty of work is under way for unarmed UAVs. The Predator, Darkstar, Global Hawk, and Outrider programs have resulted, after some turbulence, in prototypes with all of the armed services clamoring for production vehicles. The Lockheed Martin Skunk Works, for one, is known to be engaged in additional black UAV projects.[44] The Navy is also studying a UAV to loiter carrying not only reconnaissance but also missile defense packages and stand-off weapons.[45]

"A good indicator to watch is where aerospace companies are investing their research money. Across the board, they are investigating the use of high-performance, pilotless vehicles for the most dangerous aerial combat jobs."[46] The technology exists today to produce UCAVs capable of effectively carrying out both air-superiority and interdiction missions. Moreover, UCAVs have the potential to be more cost-effective than any other air system currently owned or planned by the armed forces.

The future. "Countries conform to the will of their enemies when the penalty of not conforming exceeds the cost of conforming."[47]

In 2013, the international community has come to a head against a belligerent, fundamentalist rogue state. Possessing a massive and modern military, as well as a small but demonstrated nuclear arsenal, it invades a resource-rich neighboring country. Once again, the United States leads the military response, first to halt its offensive, and then to destroy its military capability. But this enemy is not stupid. It carefully studied past American counter-offensives, and is well-prepared to fight a war for air and space superiority. Preliminary stand-off missile attacks aimed to destroy its C^3I infrastructure, but instead demonstrated the vulnerability of cruise-missiles and the survivability of the enemy's distributed systems. Now the world braces for an inevitably bloody and protracted air war. Or so they think….

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[44] "Navy Eyes Stealthy Unmanned Aircraft," *AW&ST*, 13-Oct-97, p.27
[45] "Air arsenal ship leads naval study on UAVs," *Jane's Defence Weekly*, 6-Aug-97, p.30
[46] "Unmanned Strike Next for Military," *AW&ST*, 2-Jun-97, p.46
[47] Carmichael et al., Ch.6

It is past midnight when a forward enemy radar station detects the beginning of an air assault. A passive listening post detects bursts of radiation emitted by several aircraft cruising at high altitude, about 80km away. An active radar confirms that these are incoming Global Hawk UAVs, equipped to provide communications relay for the assault. It also detects AWACS and JSTARS aircraft loitering at 150km. The distributed communications network alerts the enemy air defenses, scrambling air intercept fighters and airborne jamming drones. The enemy's own AWACS stand off a safe distance to command their side of the battle.

An enemy radar operator sits smugly inside a bunker. His antennas serve as a beacon for anti-radiation missiles, but he is a safe distance from them.[48] Besides, antennas are cheaper than missiles. He maxes out the radar power and begins a more focussed scan to try to find the stealth craft he knows must accompany the invasion. Suddenly, his eyes widen in surprise and he zeros in on a blip. It is a small aircraft diving in on him, and it's less than 3km away. He doesn't have time to think.

One of the remote JSTARS operators did a synthetic aperture radar scan of the vicinity of this radar post and picked out the bunker. He passed the exact coordinates and target information to the remote UCAV Operations Command Queue. From there it was passed to the nearest leading interdiction UCAV, which didn't appear on radar until it popped up from its terrain-following patrol course, rolled over, and opened its weapon bays, ten seconds from the target. Confirming its location and the target, a UCAV operator authorizes weapons release. The UCAV drops a cluster bomb on the antenna area, followed by a penetrating munition right into the bunker at point-blank range. Then it closes its weapon bay doors, rolls over, and climbs into the night.

The enemy's C³I headquarters cannot see what is causing its forward radars to flicker out. Meanwhile, enemy AWACS operators are frantically trying to decipher the noise and blips flooding their screens. They get glimpses of a few aircraft loitering deep in their own territory at

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[48] Hostile operators might run only one scan so that their location cannot be interpolated [*AW&ST*, 26-Oct-98, p.46]. However, the ability to reliably acquire and range a target requires multiple scans or extended illumination.

altitudes of 15km, and hoards of others zooming in at diverse altitudes and speeds.[49] But they struggle to fix these signals long enough to pinpoint any target in particular. They send their air interceptors after the closest visible targets.

No sooner have the air interceptors pointed to engage the Global Hawks than their cockpits light up with missile warnings. Some of the squadron jets turn on their own radars to discover a swarm of planes closing in at Mach 3 from 40km away. The enemy fighters turn to engage this new threat and evade the missiles launched against them. However, they are outnumbered at least 2 to 1, and have trouble locking onto the stealthy air-superiority UCAVs at a distance long enough to get a missile off. Several enemy planes go down before they succeed in engaging the UCAVs with short-range infrared missiles—a late-generation, thrust-vectoring, Russian model. The UCAVs stop their attack and begin to passively track the enemy missile exhaust trails and ready countermeasures. Powerful onboard computers determine when a vehicle is threatened. When a locked projectile comes within 5 seconds of potential impact with a craft, the UCAV accelerates into a rolling bank to maintain a vector perpendicular to it, peaking the maneuver at up to 20Gs. Even these missiles can't keep up. They either break apart trying or else self-destruct as they lose their lock. The enemy interceptors get a moment of respite as the UCAVs are occupied evading the missiles. However, only one UCAV goes down—tracked by three missiles simultaneously from different directions, it is unable to outmaneuver them all.

The UCAVs have lost a lot of speed evading the missiles, and are now within gun range of the enemy interceptors. The enemy fighters kick in their afterburners and go after them, falling into ideal pursuit positions behind them. It looks like the relatively simple onboard artificial intelligence won't be able to save the UCAVs from the skilled pilots in the Manned Combat Air Vehicles. However, the UCAVs aren't oblivious to the threat as they activate their short-range radar and IFF (Identify Friend or Foe system). Tracking the enemy fighters, they begin to pull and roll, following the same simple tactics they used to evade the missiles. The enemy pilots strain themselves to the point of blacking out trying to stay on the UCAVs. But the UCAVs can maneuver twice as hard, and easily flit out of range as other UCAVs re-engage the fighters from

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[49] "The concept of using a seemingly random series of attacks from various directions, altitudes and times to create a well-orchestrated effect on a foe is a standard element in U.S. operational planning" [*AW&ST*, 2-Jun-97, p.51].

a distance with air-to-air missiles. Soon, the distracted interceptors are falling out of the sky. The few that remain of the original squadron try to flee the encounter, only to be chased down by as many as 5 UCAVs each.

By now, some of the Global Hawks, the primary communications link in the offensive, are lost to long-range air-to-air missiles. Also, the enemy has activated airborne and powerful ground-based jammers. Without a direct line of communication to receive target and weapons authorizations, the UCAVs would turn to fly home. However, they are still within line-of-sight with the AWACS, and when they lose range with that, fall back on satellite communication links. Even if that link is disrupted or jammed, the passive Darkstar reconnaissance UAVs orbiting high overhead can assume an active line-of-sight communications relay role.

Now the battle moves further behind the enemy lines. With no other interceptors to contend with, the air-superiority UCAVs speed towards the enemy AWACS. As they do, SAM sites wake up and begin launching against the interdictors. The UCAVs leave their trajectory as necessary to evade the missiles. The vast majority succeed in doing so and return to their assigned path. However, not only every missile launch, but also every radar scan and jamming emission is detected by multiple agents in the U.S. airborne network, and broadcast to the central command. There the data is sorted and compiled and made instantly available to operators, who assign the new targets to interdiction UCAVs. By the time the enemy on the ground hears an approaching jet, it will have received authorization and be releasing its munitions.

As dawn breaks, the U.S. has struck all of its strategic targets. The enemy has lost its entire air interceptor force, as well as most of its active air defense network. It has expended enormous quantities of ordnance and succeeded only in destroying a small number of unmanned air vehicles, none worth more than $15 million.

Conclusion. The assumptions in this paper have been very conservative. All performance figures listed here are unclassified, and it is very likely that better performance has been achieved with secret systems. (Nevertheless, given the difficulties just being ironed out in the unclassified UAV programs, it seems unlikely that a UCAV as described here has been produced yet, even in secret.) In all of the scenarios and cost analysis the enemy has been given the benefit of the doubt.

Interdiction and air-superiority UCAVs have the potential to transform conventional war. If the United States were equipped with a massive UCAV force, it is unthinkable that any nation would undertake a full-scale offensive in which it might be opposed by such an overwhelming phalanx of essentially expendable fighters.

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