Hypermanoeuvrability and visual cloaking: new adaptive aerostructures technologies for UAVs

R. Barrett
Adaptive Aerostructures Laboratory
University of Kansas
Lawrence
Kansas, USA

ABSTRACT

The paper begins with a summary of the performance characteristics of the most important classes of adaptive aerostructures which are relevant for UAVs and the materials which drive them. The paper describes several classes of UAVs that take advantage of the various kinds of adaptive aerostructures technologies. These technologies are shown to be suitable for very small and even hard-launched UAVs, hovering, high speed, low speed and convertible UAVs (i.e. UAVs that can transition between helicopter and aircraft/missile flight modes). The first class of UAVs presented highlights newly invented post-buckled precompressed (PBP) actuators which are particularly well suited to enhancing convertible coleopters or 'ultra-high performance UAVs.' These UAVs are capable of hovering for extended periods of time as a helicopter in gusty, windy, dusty, real tactical environments, then popping up, converting and dashing out like a missile at several hundred knots. The paper shows photos (i.e. no computer simulations) of convertible coleopter launches from armoured vehicles, a battle-damage assessment exercise and a live fire sequence with 40mm munitions. The paper concludes with a description of the visual signature suppression (VSS) system which was employed on a 2m UAV. The VSS system was shown to suppress the visual cross section to below $1 \cdot 8\text{cm}^2$ which is the threshold for human aircraft observation. Accordingly, VSS equipped aircraft are said to 'disappear' in mid flight.

1.0 INTRODUCTION AND BACKGROUND

This paper is intended to act as an information conduit from the adaptive aerostructures branch of the aerospace industry to the greater UAV community. For nearly a decade, several important families of breakthrough technologies have been methodically matured for other subsets of the aerospace industry outside of the UAV community, including: (*i*) how to harden ever smaller actuation systems for hard-launched UAVs, (*ii*) how to design advanced flight control systems for UAVs that can hover like helicopters and fly as fast as tactical missiles, and (*iii*) the knowledge of how to make aircraft visually disappear. These breakthroughs are enabled and enhanced by various kinds of adaptive materials, including piezoelectric, shape-memory-alloy and optically adaptive polymers. Although these breakthroughs have been publicly presented in open conference and the open literature (and are therefore not restricted), few contacts have been made directly with the UAV community to transfer this technology until now.

For nearly a hundred years, the fundamental properties of piezoelectric elements have been successfully modelled. Many different classes of actuators from sonar to stereo tweeters to helicopter rotor blade elements have been made using piezoelectric sheets, stacks and blocks as driving elements[1]. Numerous studies have been centered on the addition of various types of mechanisms, the use of

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different lamination techniques and/or shapes to amplify either deflection at the expense of force or force at the expense of deflection with the earliest relevant work dating to the mid-’80s[2-8]. In each case some finite amount of total work was lost in the conversion process while weight, volume, complexity and cost penalties were incurred. Because many classes of aircraft have extremely tight weight, volume and performance requirements, they tend to drive actuators to smaller packages with higher levels of performance. Several other classes of piezoelectric actuators to be investigated as of late employ dynamic effects of oscillating piezoelectric, electrostrictive and/or magnetostrictive elements in linear- and rotary-inchworm type motors. Although well suited for some applications, their system-level power densities, bandwidths, form factors and costs are currently not compatible with some of the most demanding classes of aircraft.

Among these most demanding types of aircraft are the small uninhabited aerial vehicles (UAVs), known as mini- or micro-aerial vehicles (MAVs). Similarly, guided hard-launched munitions also present similar challenges to the design engineer with bandwidths ranging in excess of 300Hz at setback accelerations of upwards of 100,000gs. In recent years, these extreme requirements in bandwidth, weight, volume, environmental and deflection requirements have lead to the development of new, high performance actuators which are specifically tailored to these types of aircraft[9-11]. Figure 1 shows the first MAV which was enabled by piezoelectric Flexspar flight control actuators.

Although these actuators have been shown to work for many classes of aircraft, their performance could be improved still further. Although previously unpublished, it is well known by those who work with many of these classes of flight control actuators, that deadband, slop and power density are often challenging issues for the design engineer to work around.

One of the most capable UAVs which has been developed to date is the XQ-138.12 The XQ-138 is designed to take-off and land vertically, hover like a helicopter, then pitch over and transition to airplane-mode flight for dash out, cruise and loiter to speeds in excess of several hundred knots. Because this class of convertible UAVs is also intended to operate in urban and forested environments in any type of weather, the demands on the flight control assembly are extremely high. Accordingly, this paper will lay out a new class of actuator which is designed to significantly enhance the overall performance of the XQ-138 while decreasing actuator weight and volume fractions thereby opening up total useful load.

Because nearly all actuator schemes which have employed piezoelectric actuators have been centered on various arrangements that trade force for stroke while degrading the total work available, a new approach is needed. In the late ’90s Lesieutre conceived a piezoelectric transformer which was designed with axially compressed piezoelectric elements[13]. The axial compression levels were close to the buckling load which effectively nulled some of the loss generating mechanism inherent in most piezoelectric actuator designs. References 13 and 14 showed that by doing this, the overall energy conversion efficiency of the entire system could be made higher than the efficiency of the raw material itself. Accordingly, this paper lays out several years of research which have been centered on improving and bringing this fundamental discovery to the aerospace flight controls community.

A final technology summary contained in this paper is centered on the use of adaptive materials in visual signature suppression systems. Since the first optically adaptive materials were employed by Alexander the Great to coordinate troop movements in the third century BCE to today, optically adaptive materials have played important roles in many industries. Optically adaptive materials and configurations have been employed in the natural world in a wide variety of kingdoms and species. Animals such as chameleons and cephalopods use chromatophores to display dynamically changing colour and reflectivity patterns for mating, camouflage or predation. Conflicts from WW2 forward have seen ground vehicles, aircraft and surface vessels treated with optically adaptive surfaces and controllable luminosity devices actively manipulating the visual signatures. Currently, several optically adaptive materials have shown that they can change their colour, reflectivity or luminosity when commanded. This paper highlights the ever-more important role of adaptive materials in the aerospace industry by laying out the uses and showing flight test data of a 2m UAV which was equipped with optically adaptive materials in a visual signature suppression system. The end goal of this effort was to show that aircraft could become essentially ‘invisible’ to the naked eye which was demonstrated concretely in a series of flight tests at a variety of altitudes with different backgrounds.

Figure 1. The Lutronix Kolibri, the world’s first VTOL MAV enabled by piezoelectric flexspar stabilators (1997).

2.0 HYPERMANOEUVRABLE AIRCRAFT FLIGHT CONTROL ACTUATORS

For more than a decade, uninhabited aerial vehicles have been flown with adaptive aerostructures for flight control. Starting with the flights of Mothra in 1994, the first aircraft to use adaptive materials for flight control, the field of adaptive aerostructures for flight control has blossomed to include rotary- and fixed-wing aircraft, subsonic, transonic, supersonic and hypersonic aircraft[3-9]. Although it has been shown that this overall class of materials works well for most flight control applications, Ref. 9 clearly demonstrates that extremely tight weight, cost and volume constraints constantly challenge the smallest classes of uninhabited aerial vehicles (UAVs).

The first micro aerial vehicle (MAV) commisioned by the US Department of Defense was the Lutronix Corp. Kolibri in 1994. This aircraft was designed with a 6in (15cm) diameter counterrotating rotor system which was driven by a single high voltage tethered electric motor. The Kolibri functioned very well with its advanced piezoelectric Flexspar stabilators because of their excellent characteristics: 14mW power consumption, 5g total weight each, 47Hz corner frequency and four individual components. With a total gross mass of just over 200g, the flight control system occupied a 10% weight fraction. This was eventually cut by another 40% over the following two years, enabling tether-free internal-combustion engine powered flight. Still, improvements over the state-of-the-art are needed to push flight control to ever lower weight, volume, power and cost fractions to enable higher performance, smaller aircraft. The Kolibri and all other aircraft which have used adaptive materials like piezoceramics for flight control have relied upon relatively conventional actuator configurations, employing conventional stoichiometries of piezoceramics like PZT-5H and –5A. These designs have formed a boundary of actuation power density in terms of weight, volume and power. Adaptive configurations like stacks, benders, extenders, steppers and mechanically amplified actuators are shown to experience fundamental limits on the amount of actuator power delivered per unit mass, volume and acquisition cost. Accordingly, this paper is devoted to describing a new approach to breech this bounding asymptote and reduce flight control weight fractions ever further down, thereby enabling and enhancing new classes of subscale aircraft.

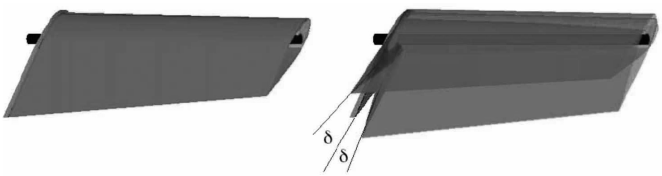

Figure 2. Configuration of the Kolibri's flexspar adaptive stabilator undergoing pitch deflections.

2.1 The actuator power density challenge

Although there are many different classes and configurations of adaptive actuators all will have several power densities of great importance to the aircraft designer. These power densities can be defined in terms of power per unit of concern, typically related to performance and/or cost constraints of the aircraft. For aircraft flight control purposes, three actuator power densities are typically weighted more than all others:

power/mass = D_{pm},
power/volume = D_{pv},
power/acquisition cost = D_{pc}.

2.1.1 Illustrative design case: The Flexspar family of flight control actuators

If one examines a typical flight control actuator like the Flexspar class adaptive stabilators used in Mothra (1994), the Kolibri (1994-97) and a host of other aircraft since then, one can see that the adaptive structures designer has several geometric variables with which trades can be made.

The driving mechanism within all Flexspar actuators is a simple cantilevered bender element. These elements may be placed mostly spanwise, chordwise or at any angle in between, used alone or in combination with other elements. Typically mostly chordwise or 'Shell-Joint Flexspar' configurations are used for high subsonic, transonic and supersonic applications or low subsonic vernier control as deflections are limited, but moment generation capability is typically high. Conversely, mostly spanwise configurations or 'Tip-Joint Flexspar' configurations are found in low subsonic applications like the Kolibri where large deflections are needed rather than large force generation capability. In either case, the main spar acts as the pivot and is collocated along the line of aerodynamic centers and the line of centres of gravity, thereby eliminating most aeroelastic coupling and limiting inadvertent buffet and detached flow deflections. In the case of the Flexspar actuators of the Kolibri, this family of Flexspar actuators were designed with a symmetric modified NACA-00xx with a thickness varying from 18% at the root to 10% at the tip, balanced about the quarter-chord. This general adaptive flight control design and associated design philosophy has been shown to be one of the most successful (and now common) approaches to date as it has flown in more aircraft than any other family of adaptive flight control devices.

Given the above configuration, the internal structure can be laid out with relative ease. Because it must be integrated into the entire aircraft system, other considerations like voltage requirements, power handling, cost and acquisition of various grades of adaptive materials must be taken into consideration. Figure 3 shows a typical trade faced by the adaptive structures designer between different actuator internal configurations.

2.1.2 Advanced actuator configurations

Although the case of the Flexspar actuators illustrates the fundamental bounds which exist in the adaptive structures design community, many other methods to expand the bounds have been tried and are currently under development. If one examines the plethora of designs in the technical community and actuators available on the open market, a handful of general categories of actuators and driving elements working to break the bounds of conventional actuator elements can be seen:

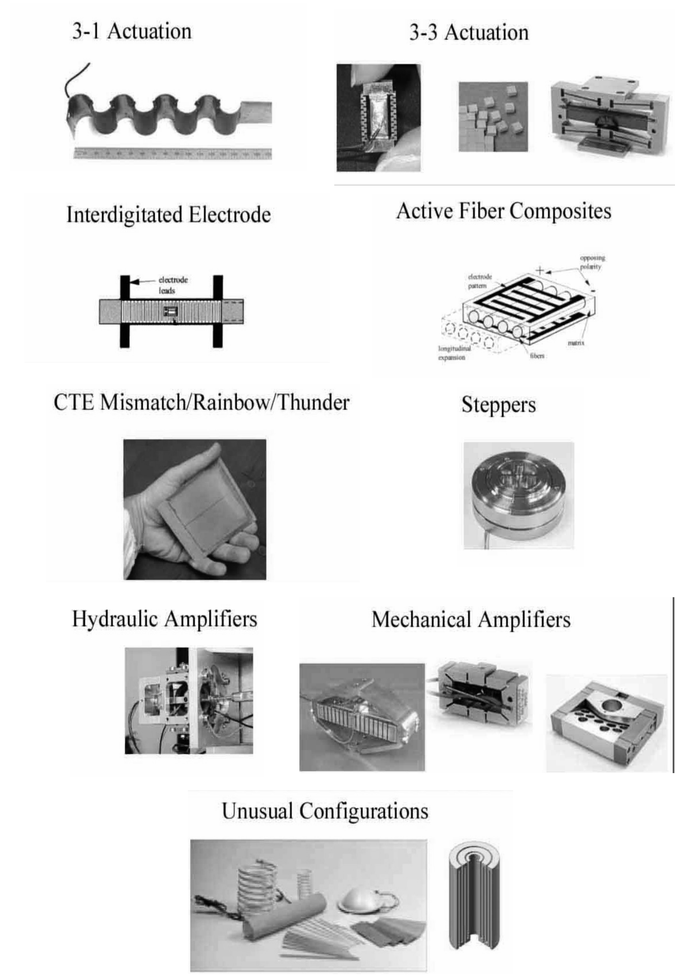

Figure 3. General categories of piezoelectric adaptive actuators.

If one considers each of the actuator families above for the job of executing flight control on MAV scale aircraft, then each actuator with its associated boundaries can be superimposed on the conventional flight control system design space. If one simultaneously constrains weight, volume and cost, then it can be seen that no single actuator class significantly break free from conventional adaptive actuator bounds.

If differing classes and stoichiometries of piezoelectric actuators are examined side-by-side, then the power density per unit cost saddle bounds formed by inexpensive tape-cast PZT-5A and –5H operating with simple 3-1 actuation will typically be more expansive than even those formed by the more energetic configurations like interdigitated electrode (IDE), active fibre composites (AFC) and even single crystal actuators. This is because the manufacturing steps necessary to produce these more advanced actuators is comparatively complicated and therefore expensive; accordingly, the power density per unit acquisition cost of these other actuator classes drive the design saddle limits closer to the design space axis.

Only stepper type actuators can significantly break the saddle limits in terms of mass and volume but under very special circumstances typically associated with low bandwidth or low-rate flight control. This generally occurs because they can take advantage of many thousands of actuation cycles during a given flight control

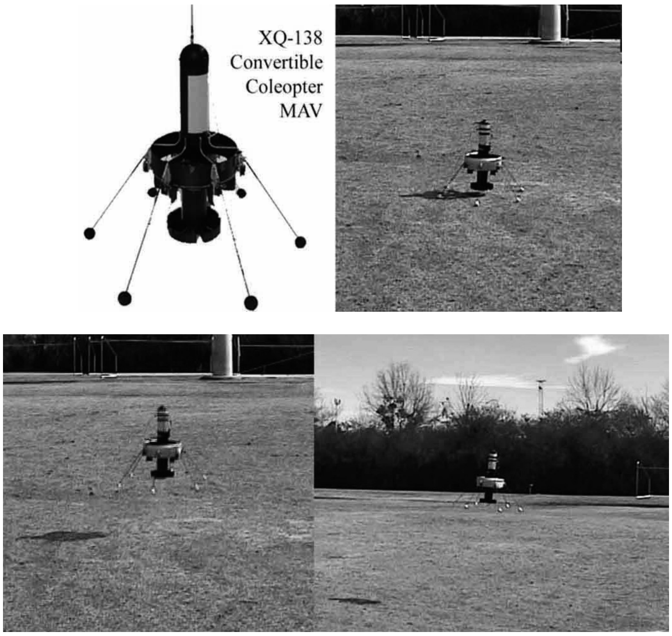

Figure 4. XQ-138 convertible coleopter during autonomy package flight testing.

surface rotation, where the other configurations are limited to only single strokes per control surface cycle. Still, given the high deflection and bandwidth requirements of MAV flight control devices, steppers are often driven to the edge of current technology. The extreme weight, volume and cost of highly toleranced interface surfaces, materials, stiff housings and driving electonics of the steppers are seen to force the design envelope of steppers closer to the origin than that of the extremely simple configurations like cantilevered bender actuators. Accordingly, a new approach is needed to significantly breech the constraining power density limits confronting aircraft flight control system design engineers. Fortunately, a new technology was just invented which is capable of crossing these boundaries. This 'Post Buckled Precompressed' (PBP) class of actuator configuration possesses up to an order of magnitude great energy and power densities (of all classes) for less than a 5% weight, volume and cost growth.

2.2 Integrated system testing

To illustrate the benefits of the PBP actuator with respect to conventional sub-microservoactuators, system-level testing was conducted. The PBP actuator was integrated into an XQ-138 airframe for flight testing. Figure 4 shows the overall configuration of the aircraft and the aircraft during autonomy package flight testing.

A system-level analysis comparing the operating characteristics of the original submicroservoactuator flight control system to the PBP flight control system showed several profound beneficial effects (see Table 1).

The profound benefits afforded by PBP actuators were enough to enable an 8% reduction in max gross weight at take-off, which could be traded for extra fuel volume enabling more than an hour of maximum power dash or hover operations.

The tremendous capabilities of the PBP actuators were protected under Ref. 15 and highlighted in Refs 16 to 19 under a variety of incarnations and flight conditions. Reference 16 showed the detailed structural mechanics of this new class of actuator elements. With respect to conventional piezoelectric flight control devices, PBP actuators were shown to be able to generate up to four times the deflection at close to 100% electrical-to-mechanical energy conversion efficiency for just a 4% weight and cost growth. More modern studies on fixed-wing aircraft showed that actuator bandwidths are actually preserved with respect to conventional piezoelectric actuators. Because this characteristic is seen as one of the greatest strengths of piezoelectric actuators, maintenance of this property is particularly critical. For comparison, a conventional electromagnetic sub-submicroservoactuator like a Cirrus CS-10BB possesses a corner frequency on the order of 3Hz, for roughly 5g of mass and peak current draws of more than 1A. The PBP equivalent draws less than 1mA, weighs less than 400mg and has a corner frequency of nearly 50Hz.

Table 1
Comparison of PBP and conventional electromechanical pitch and yaw flight control actuator systems

	Conventional Servoactuator	PBP Actuator	PBP Benefit
Max power	24W	100mW	99·6% reduction
Max current	5A	1·4mA	99·9% reduction
Mass	108 g	14g	87% reduction
Slop	1·6°	0·02°	99% reduction
Part count	56	6	9x decrease
Corner frequency	3Hz	21Hz	7x increase

To concretely demonstrate the capabilities of the PBP flight control actuators, flight tests were conducted at Redstone Arsenal, Alabama and Eglin Air Force Base, Florida. Several days of testing were conducted with a variety of armored vehicles include a US Army prototype of the Future Combat Systems (FCS) as well as a Light Armored Vehicle (LAV). Testing at Redstone Arsenal was conducted in 8kt farfield winds, light and variable at 87°F. Launches were made from the gun turret on the LAV on Test Area 1 from a remote controlled ground vehicle (with safety driver on board). Launches demonstrated a high level of controllability from both stationary and moving vehicles with a hover-to-missile flight mode transition under two seconds. Controlled landings were easily executed following reverse conversion as shown in Fig. 5.

Following testing at Redstone Arsenal the aircraft was tested under much more challenging conditions on the Hellfire Range of Eglin Air Force Base, Florida. Again, over the span of two days, launches were made from stationary platforms, fixed and moving vehicles. Pop-Up antiarmor missions were conducted from aircraft camouflaged off to the side of the road. Vehicle ID exercises were conducted as well as tandem-flying for vehicle engagement. Finally, a live-fire battle-damage assessment (BDA) exercise was conducted with an XQ-138 following a live Javelin Missile on the Hellfire range as it engaged a target T-60 tank. Flight tests were conducted in 96°F weather with winds strong and gusting to 28kt farfield. Local winds were in excess of 26kt. Such high wind conditions coupled with flight in close proximity of ground targets highlighted the inherent stability of the XQ-138 configuration as well as control authority and actuator bandwidth.

3.0 VISUAL CLOAKING TECHNOLOGIES

For countless millenia humans have used camouflaging techniques to hide things — from dwellings to traps to hunters and prey. Still today, the fundamental desire not to be seen is highly desirable for many civil and military applications. Of course, the classic techniques of camouflage, concealment and deception (CCD) are often based on the same types of techniques used by our ancestors – hide objects or individuals of interest behind, within or underneath objects that blend in with the background. While this general principal is still in practice, a different type of approach is called for when dealing with camouflaging structures like uninhabited aerial vehicles (UAVs) against a background sky.

The concept of modern, active visual stealth has its roots in a 1943 US Navy project codename Yehudi. The intent of the program, which was highly secret at the time and came to light only in the 1980s, was

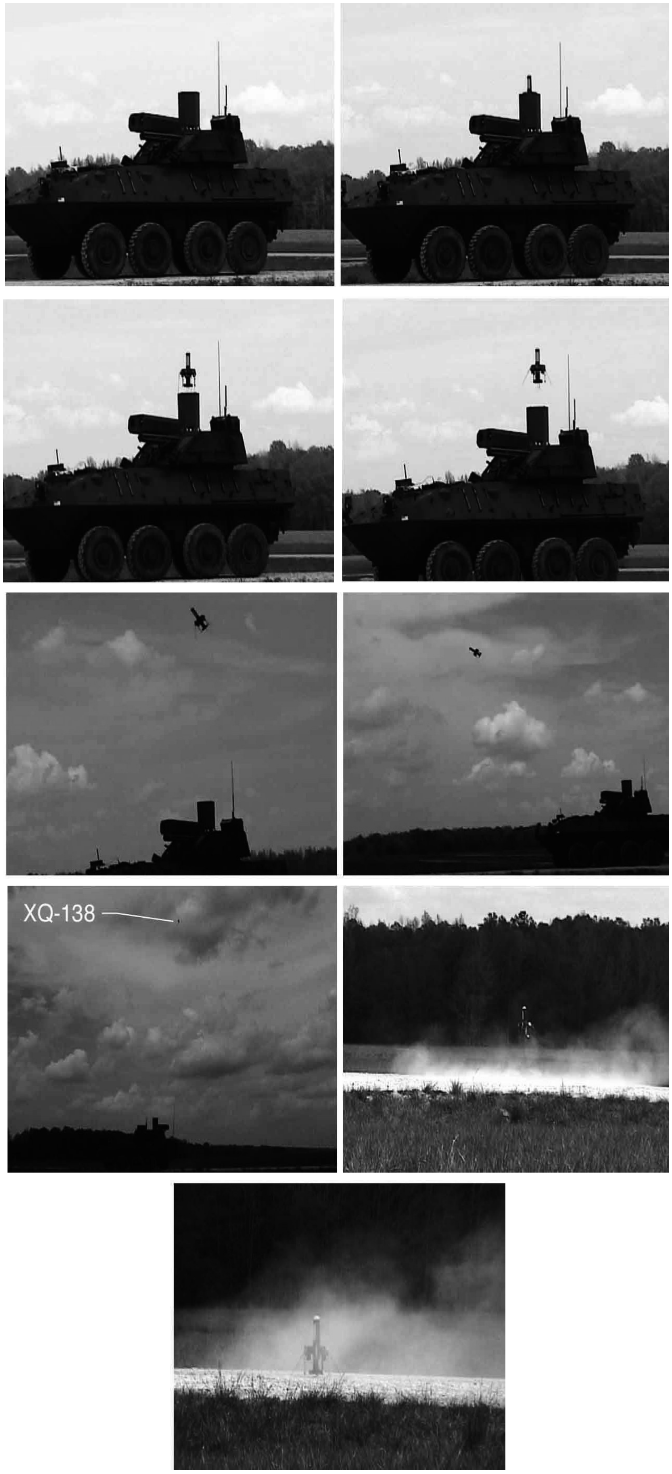

Figure 5. Launch, transition flight and landing of the XQ-138 from the US Army Light Armored Vehicle, Redstone Arsenal, Alabama.

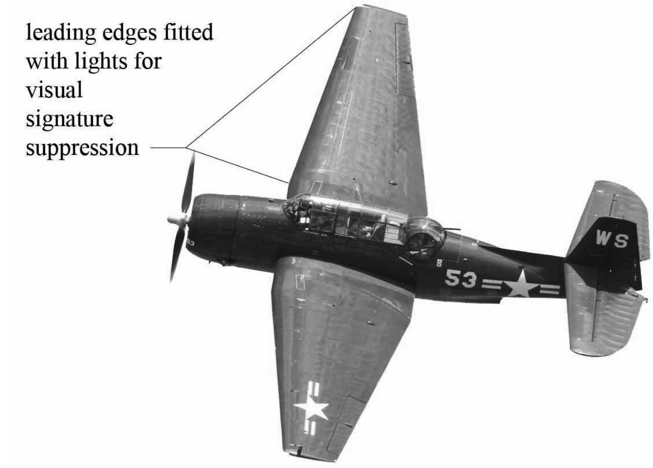

Figure 6. The first US aircraft to employ active visual stealth treatments — the Grumman TBM Avenger, 1943.

to give Navy patrol aircraft a better chance of sinking enemy submarines. During 1942, German U-boats took a heavy toll on merchant marine shipping off the East Coast of the United States. Aircraft scrambled to attack the U-boats, but submarine captains called for crash dives whenever they spotted approaching attack planes. By the time an aircraft got close enough to sink a sub, it had disappeared. Yehudi's inventors needed a way to make the aircraft harder to see, and they realised that camouflage paint wouldn't do the job: Regardless of its colour, the airplane would be a black dot against the sky. The only way to make the plane less visible was to light it up like a Christmas tree. The engineers fitted a TBM-3D Avenger torpedo-bomber with ten sealed-beam lights, installed along the wing's leading edges and the rim of the engine cowling. When the intensity of the lights was adjusted to match the sky, the Avenger blended into the background. Tests proved that the Yehudi system lowered the visual acquisition range from 12 miles to two miles, allowing the Avenger to get within striking distance of its targets before they submerged. A B-24 Liberator bomber was also modified, with similar results. Yehudi was not put into production, because better radar had already enabled Navy airplanes to regain the tactical advantage, but the idea was revived after air battles over Vietnam.

Concerned that the big F-4 Phantom could be seen at a greater range than its much smaller Russian adversary, the MiG-21, the Pentagon started a programme called Compass Ghost. An F-4 was modified with a blue-and-white colour scheme and nine high-intensity lamps on the wings and body, reducing the detection range by as much as 30%. It is most interesting to read that such offset lighting concepts are still being actively pursued today.

In addition to matching the background via differential illumination in the visible spectrum, several inventions have been conceived which work to make the aircraft wings and fuselage match the background in the infrared spectrum. Although a worthy goal, typically the thermal signatures of the propulsors generate the largest infrared signature, rather than the skin of the aircraft. Accordingly, much more effort has been and is currently being placed on suppressing the signature of UAVs in the visible spectrum.

One very interesting method of visual camouflage is through the use of fibre optic transfer mechanisms. By gathering light from one side of the aircraft, contiguous fibre optic lines can transfer that image to the other side of the aircraft. Although it consumes no power, the weight penalty is prohibitive and losses in the fibres and packing arrangement induce a prohibitive luminescence undermatch with respect to the background.

To skirt these undermatch problems, modern methods of visual stealth have used active techniques. The overall scheme is to measure the colour and luminosity of the background, then project it on the opposite side of the aircraft. A number of programmes have been centered on variants of this concept[13-17]. Although various forms of illumination mechanisms and feedback loops are described, all require relatively complicated and costly treatments which require major overhauls of the aircraft for installation. Accordingly, it is the purpose of this investigation to lay out a much less expensive method of achieving a reduced visual signature through the use of optically adaptive materials.

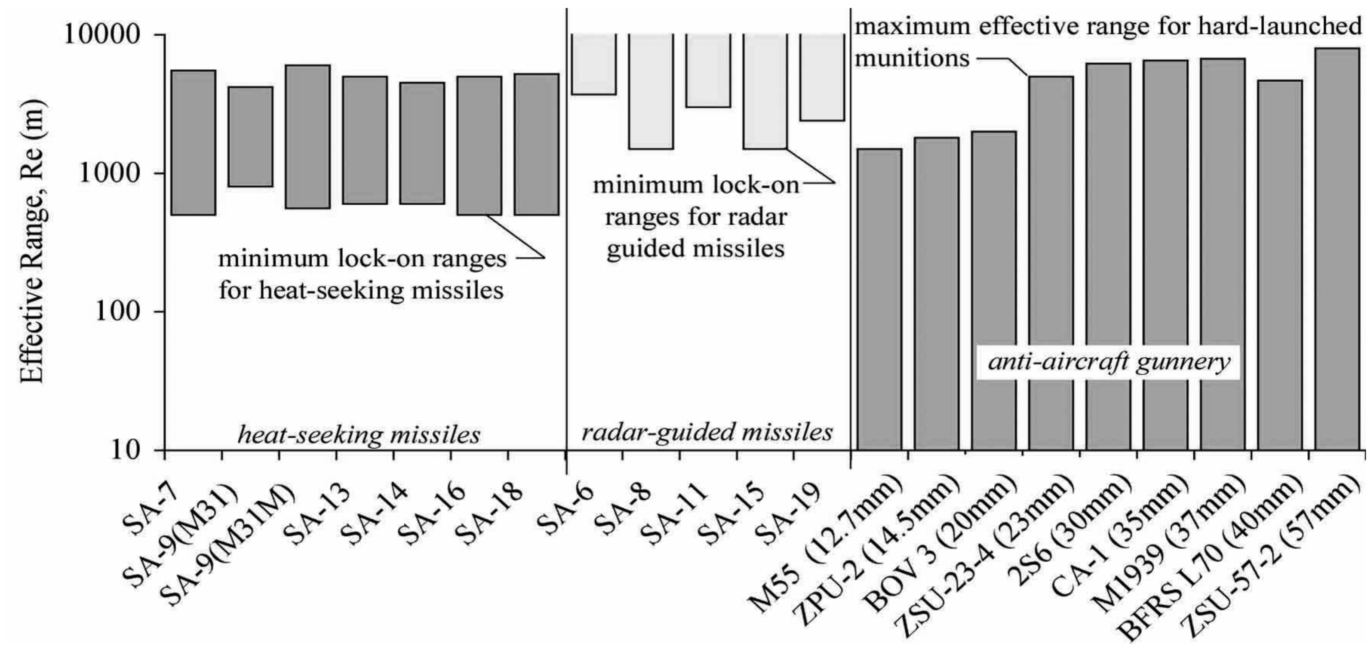

Figure 7. Effective minimum and maximum ranges of a range of anti-aircraft weapons.

3.1 Motivation

3.1.1 UAV Missions

Current challenges in global theatres pose many obstacles to tactical commanders. To keep operational costs low and yet provide real-time intelligence during close quarters operations, tactical and subscale UAVs are being used ever more frequently. From reports of service personnel, it is quite evident that the visual signatures of nearly all classes of UAVs which are currently fielded are far too high to provide an element of surprise for certain types of operations. Because some operations rely upon complete surprise, the spotting of a UAV, although not leading to loss of the aircraft, will lead to mission failure. Accordingly, visual signature suppression is absolutely critical for some missions.

3.1.2 Physical threats to aircraft at varying altitudes

In addition to mission failure, a high visual signature can lead to the loss of the entire aircraft. Because mission commanders are demanding ever closer examination of targets, operational altitudes of UAVs are being pushed lower and lower. These low operational altitudes expose aircraft to threats which are different than those experienced from aircraft operating at higher altitudes as seen in Fig. 7.

Because UAVs are operating ever more frequently at lower altitudes it can be seen that they are exiting the useful ranges for most radar- and infrared-guided missiles as they dip below 2,000ft (600m) of altitude. Indeed, several classes of UAVs are regularly operating under forest canopies, in the urban canyon and even lower. Because anti-aircraft gunnery is the weapon system of choice for engaging aircraft flying at these low altitudes, it is important to counter its guidance and tracking methods with appropriate forms of stealth. Because human ears and eyes are most often used for primary detection, masking the noise and visual appearance of such aircraft is absolutely critical.

Figure 8. Gentle Lady type 6·6ft (2m) UAV VSS test aircraft type during launch and in free flight.

3.2 Visual cross section

3.2.1 Definition

After a search of the body of open technical literature, it is obvious that no suitable technical definition exists to define how much a given aircraft stands out against a background sky. After much experimentation and surveying both aircraft and human subjects, it is clear that a term and associated definition which includes physical characteristics and psycho-ocular interpretations is needed. In an effort to approach the problem of visual signature in a scientific manner, a new technical term has been developed:

Blue-Sky overhead visual cross section (BSOVCS):

The Blue-Sky overhead visual cross section of an aircraft at a given flight state is deemed to be the area of a silhouetted lampblack disk at 100m altitude directly overhead against a cloudless blue sky at less than 50% humidity with the sun at a 40° to 50° angle to the disk-aircraft-observer plane such that the majority of a statistical sample of no fewer than ten observations from individuals with 20-20 vision declares the disk to be just as obvious as the observed aircraft, given a

10sec observation time and a flight motion of the aircraft and the disk at arc rates with respect to the observer which are representative of the aircraft at the given flight state, considering the disk and aircraft traveling in the same direction as they pass overhead.

The reader is asked to note that although the definition above allows for the scientific measurement of BSOVCS, it is still broad enough to take into account nearly all aircraft sizes, configurations, attitudes, flight speeds and levels of biomimesis. It should also be noted that the 'Blue-Sky Overhead' background is not the only measurement conditions which can and should be used to assess aircraft VCS. Accordingly, it will be important to establish uniform conditions to measure aircraft VCS against various forms of clouds from dawn to dusk against a variety of atmospheric colouration. Still, for the purposes of this investigation only, the BSOVCS is proposed as a 'first benchmark' for determining the VCS of an aircraft at a given flight state.

3.2.2 Measurement

To implement the definition above, a sampling of subjects must be recruited and their vision tested. Unlike RCS or IR signature testing, BSOVCS testing takes into account not only the physical characteristics of the aircraft, but also the psycho-optical human response to such stimulation. Subjects are seated and told which areas of the sky to watch on a cloudless, blue sky day with the sun at angles from 40 to 50deg from a vertically oriented flight plane extending from the observer vertically. The subjects are asked to turn away from the sun so that they are not partially blinded by its glare. A glass panel with a scaled lampblack dot is placed 30cm in front of the observer. Typically, for bottom-view BSOVCS measurement of slow-flying UAVs, the aircraft is orbited above the observers while they are shown various glass plates with different dot sizes till the matching sizes are found. Once ten or more samples are taken, such that the majority of the subjects find that the aircraft and the dot are "equally obvious" the area of the dots are averaged, then multiplied by 111,111 $(100\text{m}/0{\cdot}3\text{m})^2$ to arrive at the BSOVCS for that aircraft flying at that flight state only.

3.3 Visual signature suppression (VSS)

3.3.1 VSS design and installation on 2m UAV

To demonstrate the effectiveness of active visual signature suppression, a VSS system was installed on a 6·6ft (2m) fixed-wing UAV. The 'Gentle Lady' UAV is a low subsonic aircraft powered by 2·5cc displacement internal combustion engine and is capable of reaching speeds of approximately 50ft/s (30kts, 34mph, 15m/s). The VSS system used 13mil (330μm) thick electroluminescent (EL) sheets driven up to 6kHz at up to 150V. A DC chopper inverter provided power to the EL sheets which were mounted to the underside of the wing, tail and fuselage skins with tape adhesive. High energy density lithium polymer batteries powered the inverter, which, in turn drove the EL sheets. Figure 8 shows the Gentle Lady during launch and free flight with no VSS installed on the aircraft.

The true demonstration of the system-level effectiveness is seen in flight. Figure 9 shows a close up of the VSS system operating at 5m altitude at 40V, 88V, and 120V (EI = 59Lux, 900Lux, 1,819Lux respectively).

Of course, 16ft (5m) of operating altitude is unusual for 6·6ft (2m) class UAVs. Accordingly, tests were also conducted to show the effectiveness of the background match at 1,000ft (300m). Figure 10 was recorded with a 640 x 480 camera under mixed-sky conditions so as to show the effects of blue sky and clouds at greater altitudes and distances.

Figure 10 clearly shows that the aircraft essentially disappears against the background sky. From Fig. 9, it is clear that the colour and luminescence distribution is mismatched against the sky. However, at greater distances, it is easy to see that the match of the gross luminescence or equivalent illuminance is much more important than colour match or uniformity. A close-up of Fig. 10 shows that with the system off, the UAV is clearly silhouetted against the sky, however, even with an obviously imperfect match at low altitudes, at high altitudes, the details are blurred and the aircraft effectively disappears.

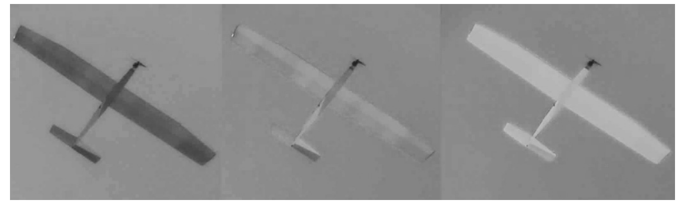

Figure 9. Luminosity undermatch, match and overmatch of VSS UAV against a mid-day blue sky, 16ft (5m) altitude.

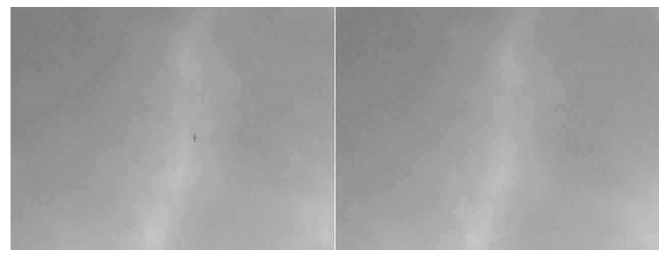

Figure 10. Luminosity undermatch and match of VSS UAV against a mid-day blue sky, 1,000ft (300m) altitude V = 88 volts, EI = 900Lux, P = 127W, f = 3,700Hz (frame resolution = 640 x 480 pixels, printed here @ 213 dpi).

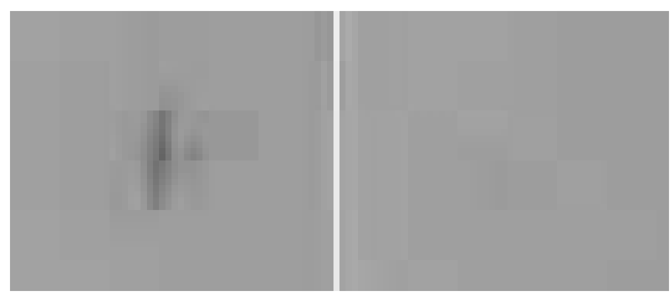

Figure 11. Zoom-in details of Fig. 10 (above) luminosity undermatch and match of VSS UAV against a mid-day blue sky, 1,000ft (300m) altitude, V = 88 volts, EI = 900Lux, P = 127W, f = 3,700Hz (frame resolution = 52 x 45 pixels).

Another demonstration that the gross effective illuminance or luminosity is more important than an accurate colour match or spot illuminance distribution is seen when the background shifts to that of a passing cloud. The whiteness of the background forms an even stronger effective surface making the dark aircraft stand out more. The background cloud of Fig. 10 concretely demonstrates that even with a white background and illumination with pale turquoise hue, the aircraft still effectively 'disappears'.

Given the definition of BSOVCS, a group of ten volunteers, each with 20/20 vision was recruited for a test. At an altitude of 1,000 ft (300m), the aircraft was illuminated at various levels. The VCS criteria of Section 3.1 was used to determine the BSOVCS quantatively. It can be seen that as the applied voltage and corresponding power consumption increased, the BSOVCS decreased till approximately 120V which is close to the middle of a weak minimum. It should be noted that 1·8 cm^2 is the averaged observed lower limit for visibility for this sample group, which ranged from 1·1cm^2 to 6·5cm^2. Figure 12 quantatively shows the aircraft disappearing with increasing power until background overmatch is achieved.

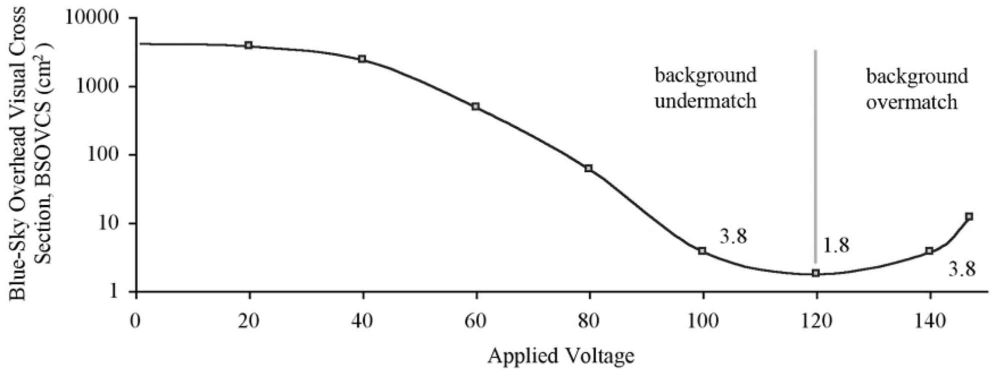

Figure 12. Blue-Sky Overhead Visual Cross Section (BSOVCS100m) with Voltage on the VSS Demonstrator UAV.

4.0 CONCLUSIONS

It can be concluded that two new branches of adaptive materials technologies presented are highly relevant for today's UAVs. The first technology is related to hypermanoeuvrable, convertible UAVs which were successfully integrated into one of the highest performance UAVs in the world. These post-buckled precompressed (PBP) actuators can provide much higher bandwidths per unit actuator weight and volume than conventional electromagnetic actuators and thereby lend to the aircraft they are integrated into vastly superior performance to other UAVs on of the same class. The second class of adaptive materials is optically adaptive. These optically adaptive materials were fitted to a 2m UAV and flown with a sensor system which allowed the illuminance of the undersides to be adjusted to match the sky. Flight testing showed that the aircraft can be made to possess visual cross sections of under 1·8cm^2 which is the lower threshold of the human eye. Accordingly, the aircraft was said to 'disappear' in flight.

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REFERENCES

1. CRAWLEY, E.F. and DE LUIS, J. Use of piezoelectric actuators as elements of intelligent structures, *AIAA J*), October 1987*,* **25**, (10), pp 987-997.
2. BAZ, A. and POH, S. Performance of an active control system with piezoelectric actuators, *J Sound and Vibration*, 22 October 1988, **126**, (2), pp 327-343.
3. PRECHTL, E.F. and HALL, S.R. Design of a high efficiency, large stroke electromechanical actuator, *J Smart Materials and Structures*, 1999, **8**, pp 13-30, IOP Publishing, Bristol, UK.
4. MOSKALIK, A.J. and BREI, D. Analytical dynamic performance modeling for individual C-block actuators, *J Vibrations and Acoustics*, 1998, **121**, pp 221-230.
5. MOSKALIK, A.J. and BREI, D. Force-deflection behavior of piezoelectric C-block actuator arrays, *Smart Materials and Structures*, 1999, **8**, pp 531-543.
6. ERVIN, J. and BREI, D. Recurve piezoelectric-strain-amplifying actuator architecture, *IEEE/ASME Transactions on Mechatronics*, December 1998, **3**, (4), pp 293-301.
7. CLEMENT, J., BREI, D., MOSKALIK, A. and BARRETT, R. Bench-top performance characterization of a C-block driven active flap system, 1998, 39th Structures, Structural Dynamics and Materials Conference 20-23 April 1998, Long Beach, CA, Paper AIAA-98-2039, American Institute of Aeronautics and Astronautics, Washington, DC, USA.
8. SCHWARTZ, R.W., LAORATANAKUL, P., NOTHWANG, W.D., BALLATO, J., MOON, Y. and JACKSON, A. Understanding mechanics and stress effects in rainbow and thunder actuators, *SPIE Smart Structures and Materials*, *Active materials: Behavior and Mechanics*, 2000, **3992**, (363).
9. BARRETT, R., BURGER, C., and MELIAN, J.P. Recent advances in uninhabited aerial vehicle (UAV) flight control with adaptive aerostructures, 2001, Fourth European Demonstrators Conference, 10-15 December 2001, Edinburgh, Scotland.
10. BARRETT, R. and LEE, G. Design criteria, aircraft design, fabrication and testing of sub-canopy and urban micro-aerial vehicles, 2000, AIAA/AHS International Powered Lift Conference, 1 November 2000, Alexandria, VA, USA.
11. BARRETT, R. and STUTTS, J. Development of a piezoceramic flight control surface actuator for highly compressed munitions, 1998, 39th Structures, Structural Dynamics and Materials Conference, 20-23 April 1998, Long Beach, CA, Paper AIAA-98-2034, American Institute of Aeronautics and Astronautics, Washington, DC, USA.
12. BARRETT, R. Adaptive aerostructures, improving high performance, subscale military UAVs, 2004, 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, 12th AIAA/ASME/AHS Adaptive Structures Conference, 19-22 April 2004, Palm Springs, CA, USA, AIAA paper 2004-1886.
13. LESIEUTRE, G.A. and DAVIS, C.L. Can a coupling coefficient of a piezoelectric actuator be higher than those of its active material?, *J Intelligent Materials Systems and Structures*, 1997, **8**, pp 859-867.
14. LESIEUTRE, G.A. and DAVIS, C.L. Transfer having a coupling coefficient higher than its active material, 22 May 2001, US Pat 6,236,143.
15. BARRETT, R. and TISO, P. PBP Adaptive actuator device and embodiments, 18 February 2005, International Patent Application number PCT/NL2005/000054, via TU Delft.
16. BARRETT, R., VOS, R., TISO, P. and DE BREUKER, R. Post-buckled precompressed (PBP) actuators: enhancing VTOL autonomous high speed MAVs, 2005, 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, 18-21 April 2005, Austin, TX, USA, Paper AIAA-2005-2113.
17. VOS, R., DE BREUKER, R., BARRETT, R. and TISO, P. Morphing wing flight control via post-buckled precompressed piezoelectric actuators, *AIAA J Aircr*, 13 June 2006.
18. BARRETT, R., MCMURTRY, R., VOS, R., TISO, P. and DE BREUKER, R. Post-buckled precompressed piezoelectric flight control actuator design, development and demonstration, *J Smart Materials and Structures*, October 2006, **15**, (5), pp 1323-1331.
19. DE BREUKER, R., VOS, R., BARRETT, R. and TISO, P. Nonlinear semi-analytical modeling of post-buckled precompressed (PBP) piezoelectric actuators for UAV flight control, 2006, 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 14th AIAA/ASME/AHS Adaptive Structures Conference, 1-4 May 2006, Newport, RI, USA, AIAA-2006-1795.