Adaptive aerostructures: the first decade of flight on uninhabited aerial vehicles

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ABSTRACT

Although many subscale aircraft regularly fly with adaptive materials in sensors and small components in secondary subsystems, only a handful have flown with adaptive aerostructures as flight critical, enabling components. This paper reviews several families of adaptive aerostructures which have enabled or significantly enhanced flightworthy uninhabited aerial vehicles (UAVs), including rotary and fixed wing aircraft, missiles and munitions. More than 40 adaptive aerostructures programs which have had a direct connection to flight test and/or production UAVs, ranging from hover through hypersonic, sea-level to exo-stratospheric are examined. Adaptive material type, design Mach range, test methods, aircraft configuration and performance of each of the designs are presented. An historical analysis shows the evolution of flightworthy adaptive aerostructures from the earliest staggering flights in 1994 to modern adaptive UAVs supporting live-fire exercises in harsh military environments. Because there are profound differences between bench test, wind tunnel test, flight test and military grade flightworthy adaptive aerostructures, some of the most mature industrial design and fabrication techniques in use today will be outlined. The paper concludes with an example of the useful load and performance expansions which are seen on an industrial, military-grade UAV through the use of properly designed, flight-hardened adaptive aerostructures.

Keywords: Piezoelectric Shape Memory Alloy Adaptive Flight Control Uninhabited Aerial Vehicle

NOMENCLATURE

Symbol	Description	Units
E	stiffness	GPa, (msi)
M	Mach number	~

Subscripts

L	longitudinal
T	transverse

Acronyms

AAL	The Adaptive Aerostructures Laboratory
AFOSR, AFRL	US Air Force Office of Scientific Research, Air Force Research Lab
AMCOM	US Army Aviation and Missile Command
ARO	US Army Research Office
DAP	Directionally Attached Piezoelectric
DARPA	Defense Advanced Research Projects Agency
DoD CDTO	Department of Defense CounterDrug Technology Office
FEM	finite element methods
FCS	Future Combat System
LAV	Light Armored Vehicle
MAV	micro aerial vehicle
NSF	National Science Foundation
PZT	lead zirconate titanate
SMDC	Space and Missile Defense Command
TACOM-ARDEC	US Army Tank-Automotive and Armaments Cmd/Armament Rsc., Dev. and Engineering Center
TNO	Toegepast Natuurwetenschappelijk Onderzoek
TU Delft	The Technical University of Delft, Netherlands
UAV	uninhabited aerial vehicle
WL	Wright Laboratory

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1. INTRODUCTION

A decade ago, the first UAV using adaptive materials for all flight control took the air. Equipped with all-moving piezoelectric Flexspar stabilators, this 1.2m (4 ft) span powered glider named *Mothra* demonstrated that these materials could be used to steer an aircraft through the air. Like many technical endeavors, *Mothra* was just an evolutionary step in a line of advances that stretched from small benchtop specimens to fielded UAVs. More than 40 adaptive aerostructures endeavors draw a direct lineage to and/or have had an impact on flightworthy UAVs. These programs have been sponsored by a myriad of agencies and institutions and vary widely in shape, size, flight regimes, design, modeling tools and testing techniques as shown in Table 1.

Table 1 Summary of Adaptive Aerostructures Projects with Direct Connections to Flightworthy Adaptive UAVs

	Project *p=piezoelectric, s=shape memory alloy c=component testing only f=flight tested v = entire vehicle configuration tested with adaptive device*		**Modeling Techniques**		**Test Techniques**			**Agency/ Sponsor**
			closed	FEM	Bench	Stand/ Tunnel	Flight	
1	Bending-Twist Coupled Aeroelastic PZT Plate (1985-87)	*c,p*	*		*	*		*MIT*
2	Adaptive Flap (1987-89)	*c,p*	*		*	*		*MIT*
3	Twist-Active Subsonic DAP Missile Wing (1989-90)	*c,p*			*			*ARO*
4	Twist-Active DAP Rotor (1990-91)	*c,p*	*		*			*ARO*
5	Aeroservoelastic Twist-Active Wing (1990-92)	*c,p*	*					*Purdue*
6	Twist-Active Supersonic DAP Wing (1991-92)	*c,p*			*			*KU*
7	Constrained Spar Torque-Plate Missile Fin (1991-92)	*c,p*	*		*	*		*KU*
8	Free-Spar DAP Torque-Plate Fin (1992-93)	*c,p*	*		*			*KU*
9	Pitch-Active DAP Torque-Plate Rotor (1992-93)	*c,p*	*		*			*KU*
10	Subsonic Twist-Active DAP Wing (1993-94)	*c,p*		*	*			*WL/MNAV*
11	Subsonic Twist-Active SMA Wing (1993-94)	*c,s*		*				*WL/MNAV*
12	Subsonic Camber-Active DAP Wing (1993-94)	*c,p*		*				*WL/MNAV*
13	Subsonic Camber-Active SMA Wing (1993-94)	*c,s*		*				*WL/MNAV*
14	Supersonic Twist-Active DAP Wing (1993-94)	*c,p*		*	*			*WL/MNAV*
15	Supersonic Twist-Active SMA Wing (1993-94)	*c,s*		*				*WL/MNAV*
16	Supersonic Camber-Active DAP Wing (1993-94)	*c,p*		*				*WL/MNAV*
17	Supersonic Camber-Active SMA Wing (1993-94)	*c,s*		*				*WL/MNAV*
18	**UAV with Flexspar Stabilator (*Mothra* 1993-94)**	***v,f,p***	*		*	*	*	*AAL*
19	Flexspar TOW-2B Wing (1993-94)	*v,p*	*		*	*		*NSF*
20	Solid State Adaptive Rotor (SSAR) (1994-95)	*c,p*	*		*	*		*NSF*
21	Aeroservoelastic Flexspar Fin (1994-95)	*c,p*	*		*	*		*AAL*
22	**UAV with Solid State Adaptive Servopaddle Rotor (95-96)**	***v,f,p***	*		*	*	*	*NSF*
23	**MAV with Flexspar Stabilator (1994-97)**	***v,f,p***	*		*	*	*	*DoD CDTO*
24	Barrel-Launched Adaptive Munition (1995-97)	*v,p*	*		*	*		*AFOSR*
25	Smart Compressed Reversed Adaptive Munition (1995-97)	*v,p*	*		*	*		*WL/MNAV*
26	Monolithic Rotationally Active Linear Actuator (RALA1995-97)	*c,p*	*		*	*		*WL/MNAV/Boeing*
27	Pitch-Active Torque-Plate Wing (1997-98)	*c,p*	*		*	*		*AAL*
28	Range-Extended Adaptive Munition (1998-99)	*v,p*	*		*	*		*DARPA*
29	Hypersonic Interceptor Test Technology (1998-2000)	*v,p*	*		*	*		*SMDC/Schafer*
30	**Coleopter MAV with Flexspar Stabilators (1998-2001)**	***v,f,p***	*		*	*	*	*DARPA*
31	**UAVs with Pitch-Active SMA Wings (2000-01)**	***v,f,s***	*		*		*	*AAL*
32	Light Fighter Lethality MicroFlex Actuator (2000-01)	*v,p*	*		*	*		*TACOM/ARDEC*
33	Pitch-Active Curvilinear Fin Actuator (2001-02)	*c,s*	*		*	*		*AMCOM*
34	SC Range-Ex Adaptive Munition (SCREAM) (2000-03)	*v,p*	*		*	*		*TACOM ARDEC*
35	Thunder Multilaminate RALA Fin (2000-03)	*c,p*	*		*			*AFRL/MNAV*
36	Centerline Precompression RALA Fin (2000-03)	*c,p*	*		*			*AFRL/MNAV*
37	Center Pivot Flexspar Fin (2002-03)	*c,p*	*					*ARL*
38	**PBP StAB (2003-)**	***v,f,p***	*	*	*	*	*	*TU Delft/TNO*
39	**Convertible UAV with PBP Grid Fin (2003-)**	***v,f,p***	*	*	*	*	*	*TU Delft*
40	**Convertible UAV with PBP Turning Vane Flaps(2003-)**	***v,f,p***	*	*	*	*	*	*TU Delft*
41	**Extended-Range Gravity Weapons w/Active Wings (2003-)**	***v,f,p***	*	*	*	*	*	*AFRL/MN/Boeing*

Although details of many of these programs are unknown in the technical community (because of various disclosure restrictions), they have included rotary, convertible and fixed-wing UAV configurations ranging from hover through hypersonic, sea-level to exo-stratospheric. A summary of UAV type and Mach range with time is seen in Fig. 1.

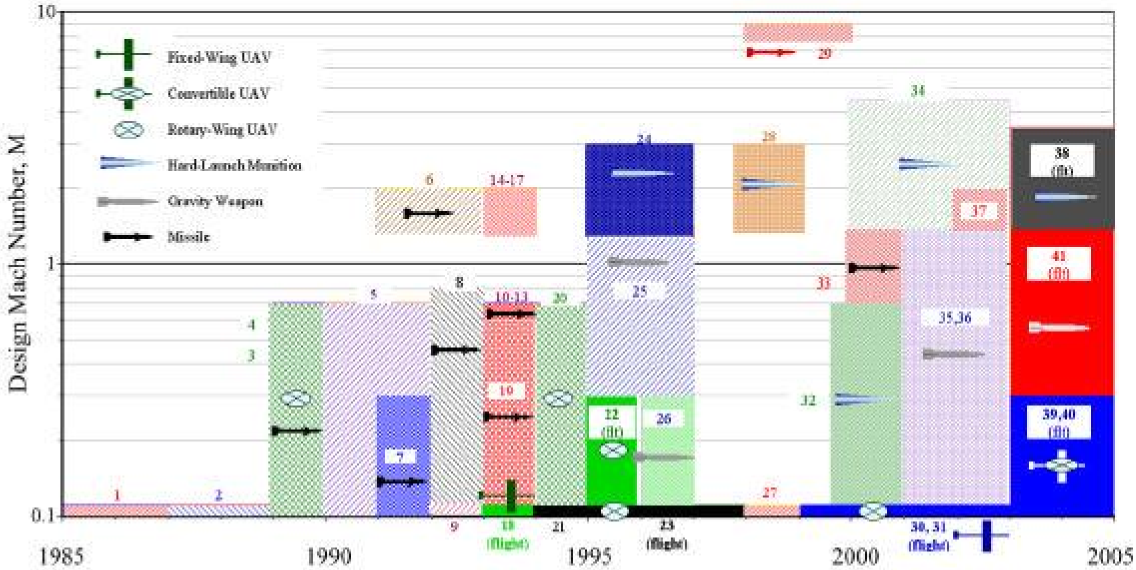

Fig. 1 Flight-Related UAV Adaptive Aerostructures Programs, Types and Design Mach Ranges with Time

2. SUPPORTING PROJECTS

2.1 Early Groundwork

Many adaptive aerostructures projects have been conducted which did not lead to flightworthy components, but were instrumental in the overall development of the technology. Fundamental design principles, modeling techniques and much interest in the technical community were established during these programs. From Fig. 1, it can be seen that the earliest adaptive aerostructures (*projects 1 & 2*) dated from the mid 1980's and were pioneered by Ed Crawley, Steven Hall and other researchers at MIT.[1-4] These early endeavors included bending-twist coupled plates which were exposed to airloads and actively bent by piezoceramic sheets which were laminated on either face of the plates. The bending deformations induced twist, which in turn, increased airloads and bending moments, eventually leading to static aeroelastic divergence. These early endeavors also included work on the first of the piezoelectric adaptive flaps which demonstrated aerodynamically useful deflection levels on the order of several degrees. The first twist-active piezoceramically actuated missile wing and helicopter rotor blades (*projects 3 & 4*) were designed and prototyped between 1989 and 1990. These structures used the concept of directional attachment which gave otherwise isotropic actuator elements (like piezoceramic sheets) highly orthotropic properties. Given orthotropy levels in excess of 100 ($E_L > 100E_T$), these Directionally Attached Piezoelectric (DAP) sheets were oriented at off-axis angles so as induce torsional shear flows to twist structures.[5-8] Although rotor blade static twist deflections of only ±0.3° were generated (i.e. not enough for flight control) because elements were only laid from the 5 to 35% chord, the full-scale DAP cruise missile wing showed ±0.8° of deflection. These deflections produced rolling moments which were enough for full roll control equivalent to many aileron configurations. Given that the wings would continuously twist without surface gapping, this also had important implications for low observables aircraft. Extensive studies on the aeroelastic properties of forward and aft swept DAP wings were made by Weisshaar and Ehlers (*project 5*).[9-11] They showed among other things that DAP wing twist deflections be controllably magnified through aeroelastic coupling generated by structural tailoring and/or wing sweep.

2.2 Supporting Munitions Projects

DAP elements made their way into a twist-active supersonic missile wing and a subsonic missile fin in 1991 (*projects 6 & 7*).[12-14] The resulting Constrained Spar Torque-Plate Missile Fin effort demonstrated ±4.5° static deflections with no aeroelastic divergence problems or use of aeroelastic amplification methods. This project represented the first time an adaptive aerostructure was built with collocated elastic axis, lines of aerodynamic centers and centers of gravity. Figure 2 shows the Constrained Spar Torque-Plate Missile Fin undergoing activation.

Although the constrained-spar torque plate design functioned very well at lower Mach numbers, the growth of the strength of the main spar with increasing Mach number also induced a similar boost in torsional stiffness. Because the main spar and the torque-plate were mechanically joined, the total deflection levels decreased as design Mach number increased. Accordingly, it became apparent that it was necessary to decouple the torque plate from the main spar to maintain good deflection performance. The resulting free-spar torque-plate fin (*project 8*) would produce the highest static pitch deflections at the time of ±7° while sporting a main spar sized for Mach 0.7 airloads.[15]

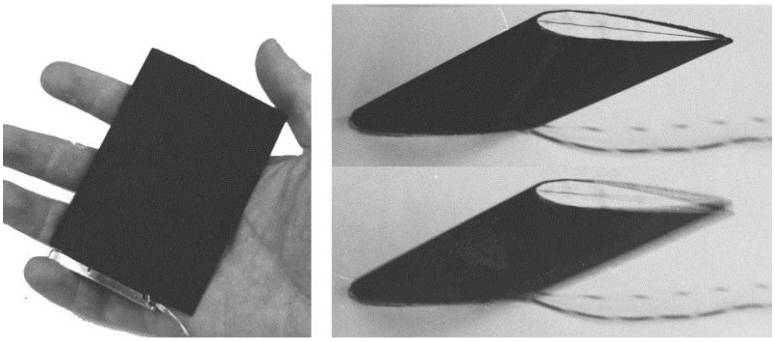

Fig. 2 Constrained Spar Torque-Plate Fin, Capable of ±4.5° Static Deflections without Aeroelastic Coupling (1991)[13]

Following the award of one of the first adaptive missile fin contracts, a number of subsonic and supersonic missile fin concepts were studied along with basic actuator characteristics which are germane to flight control.[15] These concepts included several different section subsonic and supersonic airfoil section profiles and both twist-activation and camber control, using finite element modeling techniques. Several significant conclusions were drawn from the experiences of Ref. 15. Chief among them was the realization that low aspect ratio flight control surfaces which were designed to carry full high α, high speed flight loads could not be made to actively deform enough to achieve suitable levels of flight control, even when using 10% strain actuation levels associated with shape-memory alloys for structural materials. Rather, it was shown that gross structural rotational deflections of entire flight control surfaces were necessary to achieve forces and moments which were usable for most classes of subsonic and supersonic missiles (*projects 10-17*). Figure 3 shows a 2% thick double circular arc supersonic missile fin undergoing a camber deformation beside a NACA 0012 subsonic missile fin being actively deformed in twist.

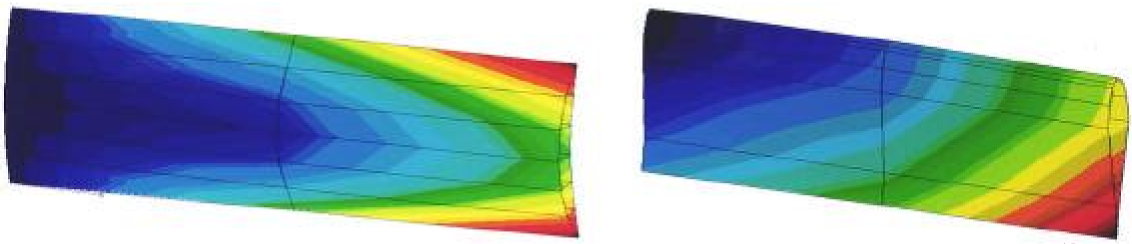

Fig. 3 Finite Element Models of Double Circular Arc Supersonic and NACA 0012 Subsonic Missile Fins (1993-94)[15]

The first full missile configuration to be tested with an adaptive wing was centered on a modified TOW-2B (*project 19*). Because nearly 1/4 of the volume within the TOW missile was devoted to flight control, there existed a tremendous opportunity to bring substantial benefits by packing all of the flight control systems within the missile wings themselves. The project showed that room for at least one more warhead would be opened up, range could be increased (with a larger spool), engagement time reduced and it would become so maneuverable that it could hit targets up to 135° off boresight.[16,17] The enabler behind the TOW-2B effort was the Flexspar solid state adaptive stabilator technology. Although invention disclosures were filed in the Fall of 1994 with the Auburn University Office of the Vice President for Research, no patents were ever applied for. This firmly cast the technology in the public domain and freed any future investigator from intellectual property revenue claims. This is liberating for the technical community at large as, to this day, Flexspar stabilators have been shown to generate some of the highest pitch deflections of any known arrangement of internally mounted adaptive stabilator actuators using piezoceramic actuator elements. Even without aeroelastic tailoring as was used in *project 20*, deflections in excess of ±30° can be achieved by these actuators.[18] Figure 4 shows the 1/3 scale TOW-2B missile model with Flexspar wings mounted in the wind tunnel just prior to testing.

Although the Flexspar technology provided good performance to missiles, a need for bolstering close-in aerial combat capabilities was identified in the US Air Force. Because the closest aerial engagements are often conducted with cannon, a program to lend guidance to air-to-air cannon shells was spawned. This marked the first time that adaptive aerostructures would be designed into munitions which would be hard-launched with setback accelerations of up to 40,000g's. The Barrel-Launched Adaptive Munition (BLAM) program was active from 1995 through 1997 and showed that a conically shaped hard-launched munition could be built to maneuver by pitching the nose section about a ball joint in the nose which was collocated at both the aerodynamic center and the center of gravity (*project 24*).[19-22] Figure 4 shows the prototype BLAM round mounted in the supersonic wind tunnel. Although the BLAM program represented the first time an adaptive aerostructure had been tested supersonically, perhaps the most important contribution to the field of adaptive aerostructures was through the establishment of manufacturing principles for piezoceramic actuator hardening.

At the same time that the BLAM program was underway, the Smart Compressed Reversed Adaptive Munition (SCRAM) effort was starting (*project 25*). Like the BLAM, it too was a munitions effort, but with a distinctly different set of design criteria. As a soft-launched area weapon, its overarching design specifications spoke to GPS guidance and maximum volumetric compression. This volumetric compression was critical to allow aircraft like the F-22 achieve respectable loadouts with weapons larger than 250lb. Because antagonistically configured piezoceramic sheets could be convienently arranged within body strakes, the robust actuators were fully capable of driving the switchblade fins a full ±10° in pitch deflection at rates in excess of 50 Hz through the entire transonic flight regime.[23,24] Again, more new territory was being charted as this was the first adaptive aerostructure to demonstrate full utility through this Mach range which is notorious for challenging actuators with its centers of pressure shifts and resulting large control moments. Figure 4 shows the SCRAM mounted in the wind tunnel prior to testing.

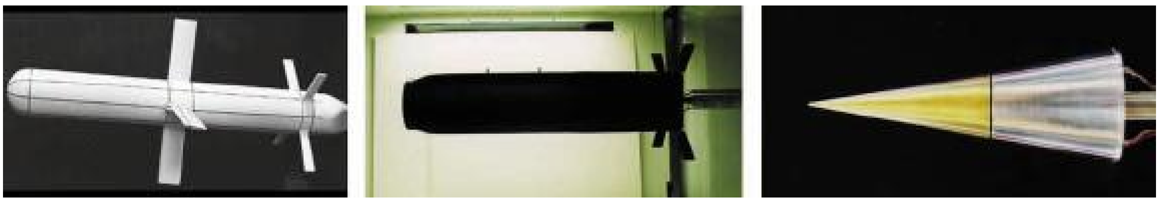

Fig. 4 1/3 Scale Adaptive TOW-2B, 1/2 Scale SCRAM Tunnel Model, BLAM Model in Supersonic Tunnel (1995-98)

Although area weapons were and are of great interest to the US Air Force, penetrators were becoming increasingly important. To meet the demands of weapon compression, several families of 250 lb penetrators of the Miniature Munition Technology (MMT) configuration have been designed for internal carriage. To aid in terminal guidance a canard kit using internally mounted piezoceramic actuators was designed using the Rotationally Active Linear Actuator (RALA) configuration for the US Air Force's WIDT program (*project 26*). Because no volume outside of the aerodynamic shells could be used to house actuators (to maintain the integrity and form factor of the penetrator head), all actuator materials were forced into the aerodynamic shell. To maintain high moment generation capability, an actuator which was capable of generating high torque levels was used. Given a constrained volume and high moment requirements, the resulting deflections were on the order of only ±2°, which is suitable for vernier control in the terminal phase. Although the program was centered on development of a new form of flight control mechanism, a series of tests which are of great importance to the technical community was conducted. These tests showed that when properly designed, an adaptive aerostructure could withstand lightning strikes up to 1.5 billion Watts and still maintain all deflection capabilities. As with the Flexspar technology, once again, invention disclosures were filed with the Auburn University Office of the Vice President for Research and again, no patents were applied for. This was beneficial to projects like the current efforts of QorTek, Inc. of Williamsport, Pennsylvania which has produced a RALA flight control surface driven by Thunder actuator sheets. Although the actuation scheme is the same as the WIDT canards, high deflections were achieved at the expense of moment generation capability. This means that rather than being usable for just terminal vernier control they are good for full flight control functions, but only through approximately Mach 0.4 as higher Mach numbers induce stabilator lock.[25,26]

In 1998 Flexspar technology was applied to a different flight regime. This time, instead of being used for low speed missiles and UAVs, it was integrated into Mach 3+ projectiles in the Range-Extended Adaptive Munition (REAM) program (*project 28*). This project would advance the field of piezoelectric actuation further by extending it to control of aerodynamic surfaces in supersonic flow around a hard-launched munition.[27,28] Bench and wind tunnel tests confirmed its utility in the mid supersonic flight range.

Although the BLAM and REAM programs ranged up to Mach 4.5, still more fantastical flight speeds were being considered. In 1998, SMDC commissioned the Hypersonic Interceptor Technology Testbed program which was designed to fly between Mach 8 and 9 (*project 29*). This program spawned hardware which deflected canted carbon-carbon fins into full Mach 9 airflows in under 4.5ms with piezoelectric elements. This demonstrated that not only were these actuators capable of inducing large moments to counter the Mach 9 flows, but they are among the world's fastest (if not the fastest) proportional missile fin actuator ever developed. Figure 5 shows the HITT test vehicle configuration and different fin deflections corresponding to various types of maneuvers.

Fig. 5 Hypersonic Interceptor Test Technology Yaw and Roll Command and Side View (1998-2000)

Following the HITT program, several efforts were concentrated on different embodiments of the Flexspar actuators including the Light Fighter Lethality and Shipborne Countermeasure Range-Extended Adaptive Munition (SCREAM) efforts (*projects 32-34)*.[29] The latest Flexspar effort used two spanwise Flexspar elements in an aeroelastically unbalanced fin configuration with a centerline spar pivot (*project 37*). With a supersonic shell configuration, airloads through the transonic will cause severe divergent pitching moments, inducing hard-over deflections and stabilator lock. Although otherwise capable of generating deflections on the same order as earlier studies, geometric binding occurs at the root (severely limiting rotations) because the actuators are not canted toward the main spar as was done in previous Flexspar designs of References 16 – 18.[30]

2.3 Supporting Rotorcraft Projects

The early 1990's saw the helicopter concepts of Ref. 7 being steadily reduced to practice. The first torque-plate rotor generated ±4.5° static pitch deflections and was capable of 3/rev individual blade control.[31] From 1991 to 1995, the torque-plate rotor concept was matured with NSF funding, eventually leading to a whirl-stand test of a 120cm (4 ft) Solid State Adaptive Rotor (SSAR). This test clearly showed that full ±8° static pitch deflections could be generated and dynamic pitch deflections could be commanded through 2.5/rev. Given a base pitch level of 4°, the rotor was capable of going from –4° to +12° which is clearly enough to achieve full flight control.[32]

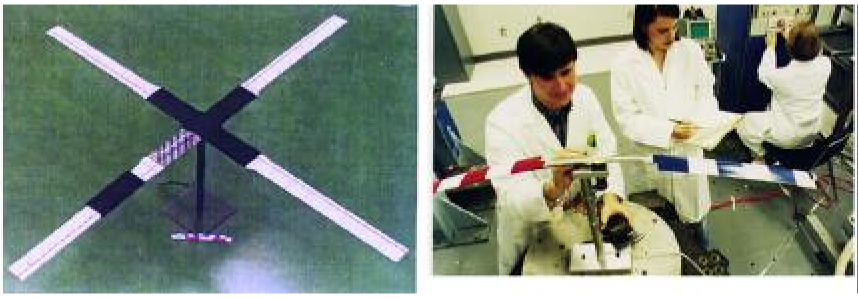

Fig. 6 The First Solid State Adaptive Rotor (±4.5° Static Pitch Deflections, 3/rev 1991) and the High Authority SSAR (±8° Static Pitch Deflections, 2.5/rev 1995)

3. ADAPTIVE UAVs

3.1 *Mothra* The First Fixed-Wing UAV to Fly Using Adaptive Materials for all Flight Control

Building upon the successes of the Flexspar technology, the world's first UAV with adaptive materials for all flight control, *Mothra*, took to the air in September of 1994. By using Flexspar piezoelectric elements with tip-extesions to drive all-flying vertical and horizontal stabilators, *Mothra* demonstrated a basic level of airworthiness under two channels of radio control. The actuators were capable of moving the stabilators more than ±14° in pitch around the main spar which was placed along the quarter-chord and the line of centers of gravity. Accordingly, there were no aeroelastic divergence or coupling difficulties in this 120cm (4ft) wing span powered glider (*project 18*).[16] Because the aircraft had a wing loading of just 17 N/m^2 (0.37 psf), it was very sensitive to adverse gust conditions. Figure 7 shows Mothra in flight and caught in a building roller (rotary gust produced by winds associated with urban terrain). Mothra logged a total of more than 100 flights demonstrating pitch and yaw control of the same order as that produced by conventional electromagnetic servoactuators.

Fig. 7 *Mothra* in Steady Flight, in a Building Roller and Empennage Showing Outline of Flexspar Actuator Element (1994)

3.2 *Gamara* The First Rotary-Wing UAV to Fly Using Adaptive Materials for All Flight Control

This effort was chartered to demonstrate that piezoelectric elements could 1) generate deflections which were large enough to produce control moments and forces which were large enough for full flight control and 2) do so at a rate of 1/rev or higher so as to act as both longitudinal and lateral cyclic control mechanisms. By using a Kyosho Hyperfly™ rotary-wing radio controlled aircraft as a baseline, a study on the comparative benefits of the Solid State Adaptive Rotor system was made. Two Hyperfly aircraft were built, one in the standard configuration with standard swash-plate servoactuator assemblies. The second aircraft was stripped of all conventional servoactuator related hardware, including the Hiller servopaddle assembly. In its place was a pair of two Solid State Adaptive Rotor torque-plate servopaddles. These servopaddles were driven in pitch by the torque plates so as to provide longitudinal and lateral cyclic commands. While possessing 3/4 of the control authority as the conventional Hyperfly, several profound benefits were seen; including, 1) a 40% reduction in flight control system weight which leads to an 8% total gross weight reduction, 2) a 26% decrease in parasite drag because the flow around the hub was cleaned up and 3) a part count reduction from 94 components down to 5.[33] Clearly, there was movement in all important system-level directions as well as a good correlation between theory and experiment. Figure 8 shows *Gamara* undergoing preflight preparations in during flight tests.

Fig. 8 Gamara Adaptive DAP Torque-Plate Servopaddle Arrangement, Preflight and Flight Testing (1996)

3.3 *Kolibri* VTOL Micro Aerial Vehicle (MAV)

In 1994 the DoD CounterDrug Technology Office commissioned what would become the first MAV program. The aircraft mission specification called for a descent into tunnels, 24 hour loiter capability, a rotor diameter no larger than 15cm (6"), low noise and live video feed. Accordingly a high efficiency, high voltage tethered electric motor was chosen to power the aircraft. The upper rotor was fixed to the motor shaft while the bottom rotor was rigidly connected to the motor housing. The entire powerplant assembly was free to rotate independent of a fixed lower fuselage via a bearing and slip-ring pair. The lower fuselage contained three axes of piezoelectric gyro stabilization, a CCD camera, structural mounts, graphite undercarriage and Flexspar piezoelectric stabilators. Newly designed lightweight Flexspar stabilators were used because of their ±11° of full static stabilator pitch deflection for only 380mg of actuator mass per stabilator. When built up into full all-flying stabilators, the entire stabilator mass including counterbalance, graphite shell, main spar and root mount was only 5.2g each.[34,35] Which is more, each stabilator was mass balanced along the pivot line which was placed along the quarter-chord of the aerodynamic shell, which nulled any aeroelastic moments and erroneous deflections which might be induced by airframe vibrations. Of even greater importance was the 47 Hz corner frequency which was needed to capture the aircraft as the open-loop time to double amplitude in pitch and roll was a mere 88ms. Fig. 9 shows the *Kolibri's* Flexspar Stabilator, *Kolibri* flight test and video camera view.

Fig. 9 the *Kolibri* MAV Flexspar Stabilator, Aircraft Configuration, Flight testing and Camera View During Flight (1997)

3.4 The Lutronix Coleopter VTOL Micro Aerial Vehicle (LuMAV)

The *Kolibri* project was followed by an effort to shed its electrical tether and fly using an internal combustion engine. The Flexspar stabilators of the *Kolibri* program were lightened to 2.7g each and fitted to a free-flying coleopter, the LuMAV. This aircraft had a total gross weight of 441g and was capable of endurances of up to 14 minutes. Like the *Kolibri*, the LuMAV flew in several different configurations and used the Flexspar stabilators because of their light weight, speed and ±11° deflection range.[36,37] The LuMAV was water hardened and could withstand 15g wall strikes. In a September 2000 fly-off at Quantico, Virginia for the DARPA MAV program, the LuMAV was the only aircraft to be airborne all three scheduled flight days, as precipitation and gusts grounded all of the other aircraft on the last day. Inclement weather testing of the LuMAV was ultimately conducted in monsoon conditions with more than 35cm/hr (14"/hr) of rainfall. Additionally, the aircraft showed stability in gusting conditions through 33 kph (18kts , 21 mph). Figure 10 shows the overall aircraft configuration, preflight and flying during the DARPA MAV fly off at Patrick AFB, Florida, 1999.

Fig. 10 The LuMAV Internal Combustion Powered MAV Structure, Preflight, and Flying at Patrick AFB, Florida (1999)

3.5 Pitch Active Shape-Memory Alloy Wing UAV

A program to evaluate the suitability of shape-memory-alloys for aircraft flight control was conducted on a 2m (6'6") powered fixed-wing UAV. The goal of the project was to demonstrate that a SMA flight control system which could generate substantially higher control moments than a conventional actuator system so as to increase maneuverability without adverse impacts on aircraft gross weight or power consumption. A study was conducted which examined more than 50 different configurations of SMA actuators. Eventually an aerodynamically balanced wing pitch mechanism was selected for the aircraft. The powered glider used 76μm (3mil) Flexinol nickel-titanium SMA wire to pitch the wings differentially up to ±2° at rates up to 2Hz.[36] As with most SMA actuators, the heating cycle went quickly with enough applied power. However, the cooling portion of the cycle was challenging within a closed wing and or fuselage. Accordingly, air ducts were routed into the fuselage to the SMA filaments. More than 20 hrs of flight testing demonstrated that roll rates were increased by nearly four fold. Fig. 11 shows the pitch actuation mechanism, preflight and flight testing.

Fig. 11 Shape-Memory Alloy Wing Pitch Actuation Mechanism, During Preflight and In Flight Test (2001)

3.6 PBP Grid Fins and Turning Vane Flaps on a Convertible Coleopter UAV

In June of 2001 a new configuration of UAV was born. This aircraft would be capable of hovering like a helicopter, then transitioning nearly 90° to fly like an airplane. The XQ-138 was intended to be more useful and maneuverable than a helicopter in the sub-canopy and urban environments and yet achieve dash speeds equivalent to those of many fixed-wing UAVs. To do this, a ring-wing coleopter configuration was chosen. In hover mode, the aircraft achieved yaw control through deflections of its turning vane flaps, pitch and roll control were maintained by a set of racking "grid" or "lattice" fins.[38] These control effectors have been shown to produce many times the normal force gradient of conventional all-flying stabilators within the same design space. They are also well known for possessing low hinge moments, aeroelastic stability and forgiving stall characteristics. Figure 12 shows the XQ-138 overall configuration and dimensions.

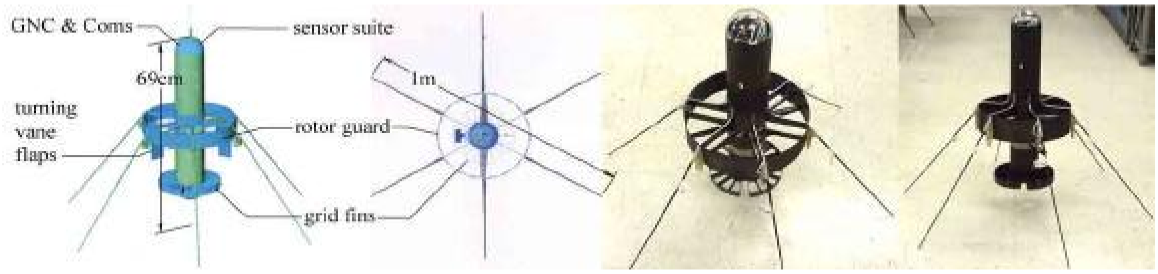

Fig. 12 The XQ-138 Convertible Coleopter (2002)

Following initial design, fabrication, prototyping and flight testing of a subscale proof-of-concept variant of the aircraft, a larger version was made during the Fall of 2001. The aircraft made its international debut at Asia Aerospace in February of 2002, executing hover, transition and fully converted flight modes. Flight testing continued through the Spring of 2002 on the US Army's Light Armored Vehicle (LAV) Future Combat System (FCS) remotely controlled prototype. Carriage and launch-related flight testing was performed at Redstone Arsenal, Alabama in the Spring of 2002, which was followed by live-fire battle-damage assessment (BDA) exercises at Eglin AFB, Florida. Figure 13 shows the aircraft during launch from the LAV.

Fig. 13 Launch of the XQ-138 from the US Army LAV Future Combat System Prototype, Redstone Arsenal, Alabama, 2002

As can be seen from Fig. 12, the aircraft contains a significant number of excressences which, although necessary for supporting various flight modes, induce significant drag increments and consume nontrivial amounts of useful load. Although the aircraft was originally designed around conventional electromagnetic servoactuators, a new class of piezoceramic actuators have been prototyped, fitted and are undergoing flight testing. These actuators employ the PBP actuator configuration which imparts a high level of robustness to the actuators, making them well suited to the military environment.[39] A simple examination of the weight fractions associated with each family of actuators shows that operating empty weight savings of 12.1% is achieved by using PBP piezoelectric actuators rather than conventional electromagnetic servoactuators, which translates to a 7.84% gross weight savings which is almost exactly the same gross weight fraction savings as achieved on the first piezoelectric VTOL UAV, *Gamara* eight years ago. It is further estimated that the switch in actuators will yield approximately a 31% drop in parasite drag, a 16 fold increase in control system bandwidth and a 96% power consumption and EMI reduction.

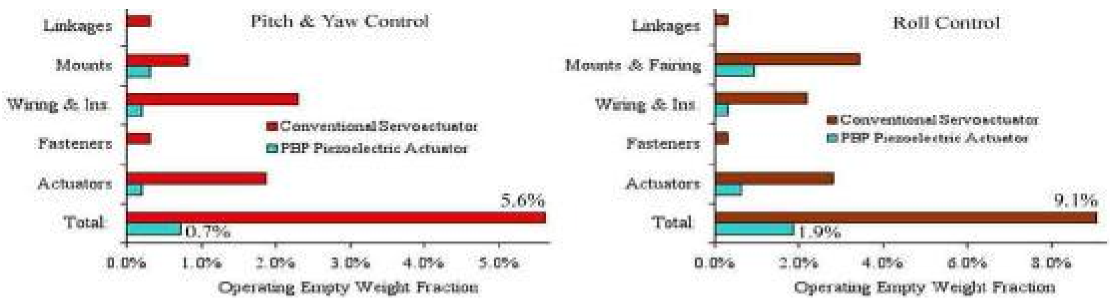

Fig. 14 Operating Empty Weight Fractions of PBP Piezoceramic Actuators and Conventional Servoactuators

CONCLUSIONS

It can be concluded that over the past two decades, more than forty adaptive aerostructures projects have had a direct connection to flight tested adaptive hardware for rotary-wing, convertible and fixed-wing UAVs. Among these programs were a handful of groundbreaking efforts which clearly demonstrated various flight control schemes using adaptive aerostructures in flight, including:

i. *Mothra* the first fixed-wing UAV to fly using adaptive aerostructures for all flight control, taking to the air in September of 1994, demonstrating that piezoelectric Flexspar stabilators generated suitable levels of force and deflection for flight control;

ii. *Gamara* the first rotary-wing UAV to fly using adaptive aerostructures for all flight control, taking to the air in December of 1996, demonstrating a 40% reduction in flight control system weight, an 8% reduction in total aircraft gross weight, a 26% drop in parasite drag and a part count reduction from 94 components to 5;

iii. *Kolibri* the world's first Micro Aerial Vehicle, using piezoelectric Flexspar stabilators to control the counterrotating electric rotorcraft in all flight modes, demonstrating that high authority, high bandwidth Flexspar flight control actuators would enable this class of subscale aircraft;

iv. *LuMAV* the world's first free-flight, rotary-wing MAV using piezoelectric Flexspar stabilators to control the aircraft in all flight modes, further demonstrating the utility of the concept;

v. *Pitch-Active SMA-Wing UAV* demonstrated a 4-fold increase in acrobatic performance;

vi. *XQ-138* Convertible Coleopter UAV demonstrating adaptive PBP actuators induce a 12% drop in operating empty weight, an 8% reduction in total aircraft gross weight, a 31% cut in profile drag, a 16 fold increase in bandwidth and a 96% reduction in electrical power consumed.

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