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THE AIRCRAFT MORPHING PROGRAM

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ABSTRACT

In the last decade smart technologies have become enablers that cut across traditional boundaries in materials science and engineering. Here we define smart to mean embedded actuation, sensing, and control logic in a tightly coupled feedback loop. While multiple successes have been achieved in the laboratory, we have yet to see the general applicability of smart devices to real aircraft systems. The NASA Aircraft Morphing program is an attempt to couple research across a wide range of disciplines to integrate smart technologies into high payoff aircraft applications. The program bridges research in seven individual disciplines and combines the effort into activities in three primary program thrusts. System studies are used to assess the highest-payoff program objectives, and specific research activities are defined to address the technologies required for development of smart aircraft systems. In this paper we address the overall program goals and programmatic structure, and discuss the challenges associated with bringing the technologies to fruition.

INTRODUCTION

Smart technologies, including sensors, actuators, and their associated support hardware and micro-electronics, have given rise to a broad spectrum of research. This research has led to a series of breakthroughs in a wide variety of disciplines that, when fully realized, have the potential to produce large increments in aircraft system safety, affordability, and environmental compatibility. We are therefore at a critical juncture in the development of individual technologies, where it is appropriate to take a serious look at integration issues, system benefit studies, and coordination of disciplinary research efforts[1].

The Airframe Systems Program Office of the NASA Office of Aeronautics and Space Transportation Technology has been developing a set of coordinated research programs in which individual disciplines are supported in a collaborative environment to foster the development of breakthrough technologies. Aircraft Morphing is a six-year program to develop smart devices for airframe applications using active component technologies. In this context a smart device senses and reacts to its local environment to achieve an overall system benefit, such as to increase performance or to maintain flightworthiness in the event of other failures. The goal of this program is to develop and mature active component technologies that can be embedded in aircraft structures and provide cost effective system benefits. Figure 1 illustrates typical targeted benefits over various flight regimes, including damage tolerance and assessment for improved safety, noise control for passenger comfort and environmental compatibility, drag reduction, lighter and simpler takeoff and landing systems, and flutter and gust alleviation for increased performance and reliability.

The development of smart devices covers a range of disciplines, and supports the integrated focus areas of

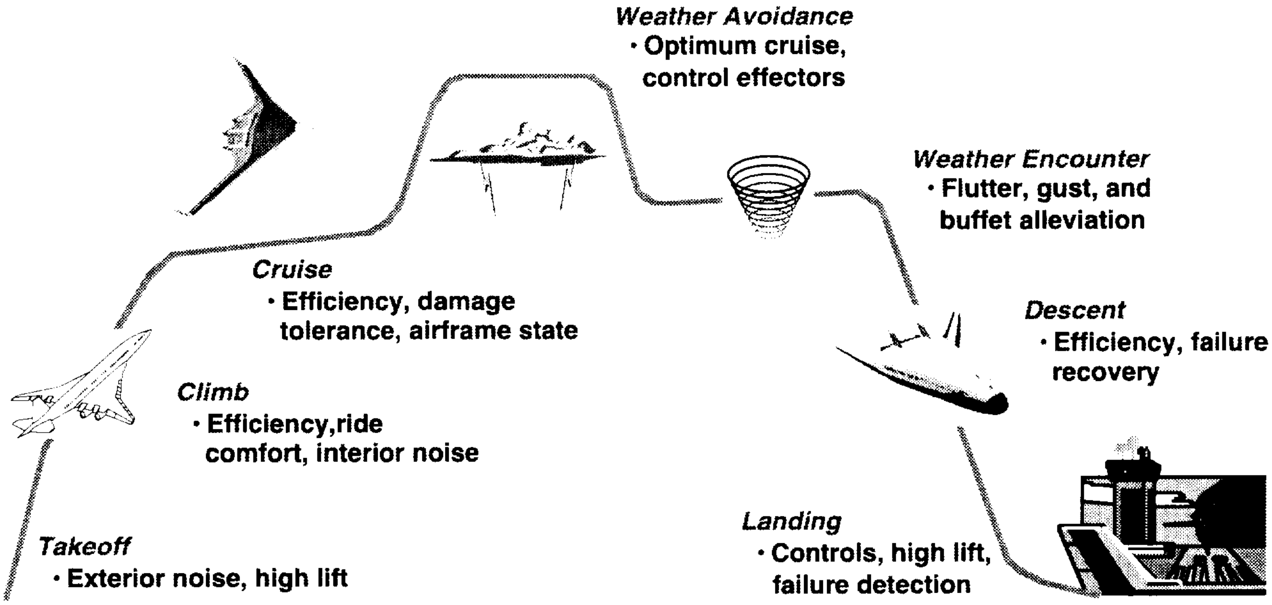

Figure 1. Range of application of active technologies

active aerodynamics, active noise control, active aeroelastic control, airframe health monitoring, and active shape control. In this program, devices based on smart materials will be developed to control structural vibration and fatigue, noise, and aerodynamics. These devices are composed of active components with localized intelligence and a high degree of local autonomy. These active components will ultimately be integrated into composite structures to reduce parts count, minimize maintenance costs, and maximize reliability.

The current state of the art in smart materials and structures might be loosely grouped into two general categories: quasi-static shape change (for example through shape memory alloys) and high bandwidth actuation (such as piezoelectric and magnetostrictive materials). The quasi-static technologies are viewed as substantially more mature, and are addressed in this program through cooperative programs with Defense Advanced Research Projects Agency (DARPA) and industry. The primary focus of the Aircraft Morphing program is to develop high-bandwidth, closed-loop devices with dynamic actuation, local sensing, and feedback control. For many applications, these devices will modify local phenomena to support a macroscopic strategy, such as flow separation control for advanced high lift systems.

Aircraft Morphing is an inherently multidisciplinary program, and has been built around a core discipline-based structure to provide the fundamental technology base. This maximizes the leveraging of all technology developed in the program, and more fully integrates the output of each part of the program. The seven disciplines are shown in Figure 2.

Active flow control technology dynamically alters the global flowfield by interacting with and controlling localized flow instabilities and flow structures. Advanced materials are being developed for sensors and actuators, as are polymers for embedding the devices into integrated structures. The smart-structures component targets aeroelastic applications using piezoelectric patches and active piezoelectric fiber composites for gust alleviation, buffet load alleviation, and flutter suppression.

Noise control and vibration suppression technologies utilize local sensing and actuation for the control of both interior and exterior noise. An integrated approach to control systems and system identification addresses the control laws and controller response required for the individual devices, as well as a global approach for distributed arrays of devices. An integration effort is targeted at actuator strategies, the development of models, and a generalized approach to implementation of multifunctional aircraft structures. At the system and airframe level, multidisciplinary design optimization will take advantage of the tools developed

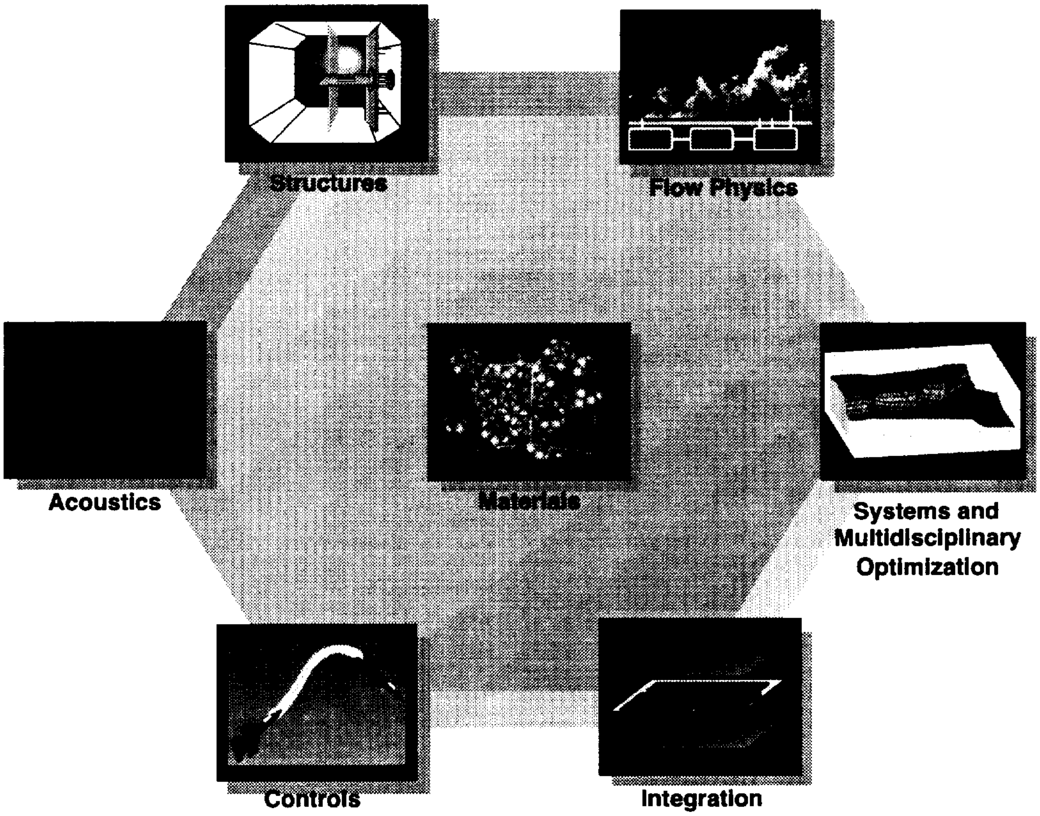

Figure 2. Aircraft Morphing integrated disciplines

within the program to optimize the component technologies and provide a systems approach to component integration.

PROGRAM GOALS AND QUANTITATIVE OBJECTIVES

The stated goal of the Aircraft Morphing program is the development of smart devices using active component technologies to enable self-adaptive flight for a revolutionary improvement in aircraft efficiency and affordability. The key words in this statement are "revolutionary improvement" in that we are focusing the technologies on specific high-benefit systems rather than merely developing the technology in an *ad hoc* fashion. In all too many programs, the results of a highly successful research effort were never implemented in real aircraft either because the cost of implementation was too high, or the benefit of the overall system improvement was too small and ultimately could not justify the risk associated with taking the system to production.

System studies will be used *a priori* to identify the applications with the highest benefit in a real operational environment. Best estimates of the technological benefits of the active components are used to sort among the various potential applications to find those with the greatest cost/benefit ratios. A first-order pass through this process has identified four quantitative targets for application of active component technologies:

a) advanced health monitoring to reduce operations and maintenance costs by 10 percent; this goal can be translated into a flight safety increment
b) active structural damping for a 30 percent reduction in wing bending loads without increasing structural weight; the key issue here is factoring in the weight of actuators and their support components
c) active noise reduction for a 3 dBA noise reduction (interior and/or exterior noise) with no weight increase
d) active flow separation control for a 15 percent decrease in high-lift system weight; active separation control has a wide variety of applications beyond that to high lift systems

Research conducted under the Aircraft Morphing program addresses each of these four goals, either directly or indirectly. Each of these goals is linked to the primary program focus of generating technologies to enhance aircraft efficiency and affordability, but which have benefits germane to a wide range of needs, including enhanced safety and environmental compatibility.

We are addressing the development of embedded sensor technologies to enable effective aircraft health monitoring and increase flight safety. Advanced health monitoring technology will reduce airframe lifecycle cost by enabling condition-based maintenance of airframe components. This has the potential of increasing aircraft safety at a lower cost than can be achieved with present day technology. Sensor technology is a spin-off of any active system in that adequate sensors, data handling, data fusion, and data processing systems must be developed before feedback control can be attempted.

We have chosen to focus the embedded sensor technology work (such as embedded fiber optic strain sensors) on airframe health monitoring. This effort includes crack and failure detection, monitoring of component strength degradation due to fatigue, acoustic monitoring, and in-situ aerodynamic data.

Component technologies that enable affordable integrated self-adaptive airframes and noise reduction will be developed to address the remaining program goals. The weight and cost of an airframe are directly related to manufacturing cost, complexity, and parts count. Direct active structural damping will enable lower-weight airframe structures. Active high lift systems ultimately can produce simpler systems with less complexity and lower weight by potentially eliminating discrete large-scale components such as flap elements or slats. Active noise control devices can reduce low frequency noise and vibration without incurring the high weight and volume penalties associated with passive damping treatments.

There are three primary focus areas for the smart devices research: active aeroelasticity, active aerodynamics, and active noise control. These three areas have the common thread of integrated sensing, actuation, and control. In active aeroelasticity, bonded piezoelectric elements are used to induce local strains to alleviate flutter and buffet. In active aerodynamics, dynamic actuators interact with the local unsteady flowfield to generate mean aerodynamic forces. In active aeroacoustics, dynamic actuators damp structure-borne sound and vibration, and modify the dynamics of noise-generating flows.

Component development is a very substantial activity spanning the entire duration of the program subelement and including advanced materials, piezoelectric development and characterization, and the integration of materials into devices. Ultimately these devices will be integrated into fully active panels, using embedded power distribution and data bus architectures. Intermediate high-level program deliverables include a demonstration of an integrated actuator panel with plug in components effective boundary layer flow control to alleviate flow separation. The final high-level deliverable occurs at program conclusion and consists of fully integrated devices for active flow control, active aeroelasticity, and active noise control.

The aeroelasticity task is focused on integration of patch type actuators into structural components for active flutter suppression. Various actuator technologies will be evaluated for wing and rotor applications, including discrete piezo patches and active fiber composites. Experimentally validated models will be used to assess actuation strategies, bench-top experiments will assist in determining feasibility and system trade-offs, and larger scale wind tunnel tests will demonstrate overall system performance

The active noise control task has a similar focus to the flow and aeroelasticity activities. Patch type components will be integrated for active structural damping with advanced control laws. Optimization approaches will be developed to minimize the number of actuators and sensors required to achieve desired noise and vibration goals. New technologies will also be investigated for suppressing noise in free jets. Localized actuators at the jet exit will be used to seed instability modes in the free jet to ultimately interfere with noise generation mechanisms.

Smart airframe design and integration tools, and system analysis will support all the program goals. We are developing design tools to facilitate the design and fabrication of active aircraft systems. The efficient design of smart aircraft components and their integration into aircraft systems requires state-of-the-art design tools for cost-effective implementation of these technologies. The requisite materials, structural, mechatronic, fluid dynamic, and acoustic modeling tools will be developed to permit the full-scale design and assessment of smart aircraft systems. Multidisciplinary analysis and optimization tools will aid the design process for these highly integrated systems. Systems analysis for full aircraft systems will determine the high-impact applications of smart technology.

KEY DISCIPLINES

Although the primary products of the Aircraft Morphing program align with the program goals, the technology inputs supporting each of these goals are discipline based. Thus the program has a hybrid management structure, in which the products of the program are generated in the integrated program subelements, but the research activities are conducted in focused discipline areas.

In this structure, the actual research activities are managed by discipline, whereas the program subelements are organized by integrated technology. This structure has two main advantages: 1) integration at the highest level, and 2) reduction of fragmentation at the research level.

A key management aspect of the program is that interdisciplinary teams will coordinate the research to develop an integrated program output. Due to the nature of this program, it is optimal to focus on disciplines at the lowest level and to produce technologies applicable to multiple subelements. This is in contrast to having multiple separate teams working similar disciplines, but targeted at individual subelements.

Materials Advanced materials are a key requirement for the development of smart airframe systems. The fundamental areas of materials research within the program are computational materials, advanced piezoelectric materials, advanced fiber optic sensing techniques, and fabrication of integrated composite structures. The computational materials effort is focused on developing predictive tools for the efficient design of new materials with the appropriate combination of properties for next generation smart airframe systems. Computational materials research can lead to an integrated approach whereby structures and materials are designed as a system that will reduce the time for development and verification of new polymer matrix composites and associated resin systems significantly.
Fiber optic sensors are being developed for monitoring critical structures on future aircraft that are expected to be largely carbon fiber reinforced composite structures [2]. Methods for embedding the optical fibers in these composites are being investigated. With embedded sensors, composite cure can be monitored, leaving the sensors as an integral part of the structure for health monitoring. For structural health monitoring, advanced nondestructive evaluation techniques including optical, thermal, ultrasonic, and radiographic will be developed for detection of delaminations, disbonds, cracks and environmental deterioration in aircraft structures. Other parameters of interest are aerodynamic quantities such as flow and pressure and conformation of aerodynamic surfaces.

Piezoelectric devices are one of the most promising actuator technologies for the implementation of active boundary layer control, high bandwidth noise suppression, and aeroservoelastic tailoring. However, many potential aerospace applications require displacement performance larger than what is achievable in conventional piezoelectrics. Recently researchers have developed two high-displacement piezoelectric actuator technologies, RAINBOW (Reduced And INternally-Biased Oxide Wafer)[3,4] and THUNDER (THin layer composite UNimorph ferroelectric DrivER and sensor)[5] to meet these requirements. These devices are unimorph-type actuators that consist of a piezoelectric ceramic layer bonded to one or more non-piezoelectric secondary layers. Because of the use of elevated temperatures during processing, internal stresses are created in the structures that significantly enhance displacement through the thickness of the devices. In this program research will be completed to develop a mechanical model of these high-displacement actuators to optimize their performance in configurations for vibration suppression, noise cancellation, and flow control and to increase the force output of these bender actuators. Other research on piezoelectric actuators includes the development of integrated piezoelectric thin films with MEMS structures to produce miniaturized actuators with sufficient force/strain properties for aircraft flow control. Other research in the area of advanced piezoelectric materials involves the development of high-temperature piezoelectric polymers[6]. This work utilizes computational chemistry methods to the guide the synthesis of novel piezoelectric polymers for sensor applications.

In the area of polymer and smart composite technology, high temperature hierarchical polymers with improved electroactive, adhesive, and composite properties for use in fabricating integrated airframe structures and components will be developed. Innovative fabrication techniques for processing structural composites with sensor and actuator integration will be developed. Efficient and cost effective techniques will be investigated for processing composite components utilizing the proper combination of matrix resin, carbon fiber, sensor and actuator materials and cure methods.

Smart Structures Aeroelasticity is the study of the interaction of structural, aerodynamic, and inertial forces. These forces are present on all aircraft and rotorcraft and strongly influence the design of all flying vehicles. Successful air vehicle designs are those that have the minimum weight to accomplish the mission. However, design modifications necessary to address aeroelastic issues have typically been passive solutions resulting in reduced flight envelopes or significant weight increases or, frequently, both. Passive solutions include adding structural members for increased stiffness, adding mass or modifying geometry for improved dynamic stability. An active control approach eliminates most of the weight and performance penalties associated with the passive approach and additionally provides flexibility in that the control law and be varied with configuration or flight condition[7].

Active solutions to aeroelastic issues are focused in two areas: 1) aerodynamic control using conventional aerodynamic control surfaces or smart aerodynamic devices and 2) structural control via mechanical linkages or smart structural devices. In many cases, applications of smart devices will take advantage of the inherent flexibility in air vehicles to create more efficient structural designs. At NASA–Langley, much of the effort in the area of active control of dynamic aeroelastic phenomena is focused towards applying smart piezoelectric-based actuators for active strain actuation. Piezoelectrics are chosen because of their high bandwidth, the wealth of knowledge available on piezoelectrics and previous experience with piezoelectric-based devices. Research using other smart materials for aeroelastic control is being conducted in the Smart Wing program[8] in collaboration with DARPA, the Air Force Research Laboratories (AFRL), and the Northrop Grumman Corporation. In this program, shape memory alloys, Terfenol-D, and piezoelectric actuators are being used for wing shape control for improved aerodynamic and aeroelastic performance.

In the Aircraft Morphing program, the research on applying smart piezoelectric-based actuators to aeroelastic problems is focused toward developing the requisite enabling technologies. These enabling technologies and related in-house research efforts include developing experimentally-validated finite element and aeroservoelastic modeling techniques; conducting bench experimental tests to assess feasibility and understand system trade-offs; and conducting wind-tunnel tests to demonstrate system performance and understand application-specific issues. The key aeroservoelastic applications of this research include: active twist control of rotor blades using interdigitated electrode piezoelectric composites and active control of flutter, and gust and buffeting responses using discrete piezoelectric patches. Although the structures research in the Aircraft Morphing program is currently directed toward aeroelastic applications, the vast majority of the enabling technology research is easily applicable a wide range of applications including active acoustic control and health monitoring.

The objective of research on finite element modeling (FEM) and validation on piezoelectric actuators is to develop and validate simple and accurate techniques for modeling complex structures containing piezoelectric actuators using commercially-available FEM codes such as MSC/NASTRAN. This modeling effort will include the use of in-plane patch piezoelectric actuators as well as out-of-plane THUNDER actuators. Finite element models of structures of increasing complexity, such as composite plates, box beams, and monocoque sections will be developed and validated. Validation will be accomplished through designing, fabricating and ground testing composite structures with embedded and surface-bonded piezoelectric actuators. These experimental testbeds will also be instrumental in providing a means to evaluate a variety of control techniques to ascertain the most efficient and/or effective technique for suppressing vibration. One of the techniques being investigated in the Aircraft Morphing program is passive or active damping augmentation using shunted piezoelectric actuators[9]. This method, which uses a parallel inductor and resistor to electrically shunt the piezoelectric actuator, may provide a simple, low power alternative to active control using conventional (unshunted) piezoelectric actuators. Future research activities include conducting open- and closed-loop experimental ground tests on large-scale structures to assess trade-offs in piezoelectric control effectiveness, power consumption and optimal control strategies. This work will address both active and passive control techniques with shunted piezoelectric actuators and conventional, unshunted piezoelectric actuators. Aeroservoelastic (ASE) modeling techniques will also be developed in the Aircraft Morphing program to simulate the ASE response of a wing due to piezoelectric actuation. The air-off results of the ASE modeling effort will be validated using the above mentioned ground testbeds. Air-on results will be validated via wind-tunnel testing[10,11].

In addition to patch piezoelectric actuators, another novel piezoelectric-based actuation scheme is being studied in the Aircraft Morphing program called active fiber composites[12] (AFC). By combining an interdigitated electrode (IDE) poling technique with piezoelectric fiber composites, a high performance piezoelectric actuator lamina is created, called an "active fiber composite". This active fiber composite can achieve much larger in-plane directional actuation strains and has improved strength and conformability characteristics than that of a conventional monolithic piezoceramic. Active fiber composites may provide improved controllability for many applications. Recent analytical and experimental investigations have indicated that helicopter rotor blades embedded with AFC should be capable of meeting the performance requirements necessary for an individual blade control (IBC) system. An IBC has been shown to be among the most effective means of reducing or eliminating rotorcraft vibrations. In the Aircraft Morphing program, the enabling technologies needed to use active fiber composite for active control of aircraft and rotorcraft vibration suppression will be investigated.

Flow Control Half the weight and cost of a transport aircraft wing is in the complex high lift system. Active flow separation control can reduce the parts count, complexity, and weight of a high-lift system. Physical concepts exist for dynamic phenomena which control flow separation, viscous drag reduction, control of shock boundary interactions, three-dimensional separated flows, noise-generating shear flows, and transition to turbulence[13-16].

Effective actuation is generally the prime driver for active control strategies[17-24]. Typical approaches involve blowing, suction, or moving surfaces. In the case of the first two, a lumped system approach using pumps and ducting have made this technology impractical. In contrast, moving surfaces can be locally actuated using magnetostrictive, piezoelectric, electrostatic, or thermally driven devices.

Sensing of the flowfield and the effect of actuation on flow characteristics is the second major element of active flow control[25-28]. Sensing must be distributed over the region of interest and must be capable of measuring the appropriate flow parameters. New sensing technologies that employ MEMS, fiber optics, and integrated computing at a reasonable cost and level of reliability are a necessary precursor to the implementation of active technologies. Due to the distributed nature of sensing and actuation, the control systems must be likewise distributed rather than centrally located. Approaches to control theory that integrate models of the fluid dynamic response are under development.

Acoustics The acoustics effort under Aircraft Morphing provides operational and noise relief to the airport community and aircraft passengers and crew. Many airports restrict operations to specific hours and to specific aircraft meeting more stringent local noise certification requirements than present FAA stage 3 rules. We seek to provide a base technology to reduce the noise generated by a wide class of jet aircraft, directed to the 10 dB and 20 dB noise reduction goals. These reductions will exploit the influence of small changes in the exit nozzle geometry or the effect of localized sources of heat addition on the stability of turbulent sources of jet noise. Past studies have shown the large scale structures in the jet flow exhaust downstream of the nozzle exit can be affected by conditions in the nozzle. These changes may be effected by both static and dynamic inputs to the boundary conditions. In addition, work to control fan tones related to turbomachinery noise has been studied under other programs. This control has been implemented in one of two ways: acoustic sources in the inlet or bypass duct[29]; or source modification by application of acoustic or flow sources[30] in the vicinity of the rotor blades or stator blades resulting in an alleviation of the interaction of the two.

Work is also ongoing for the reduction of aircraft interior noise and vibration for passengers, crew, and equipment with minimum weight and space penalties. Previous work related to interior acoustics has focused on controlling tones due to propellers in commuter aircraft[31] or engine shaft tones in jet aircraft. This has taken the form of active noise control with distributions of loudspeakers in the cabin space[32], active headsets, active structural acoustic control where force actuators are applied at the engine mount system[33], or adaptive tuned vibration absorbers applied at the engine mount systems[33]. Direct control of cabin wall vibrations has also been evaluated in the laboratory and is currently the subject of much current research[34]. Past work has focused on propeller tone penetration, but much interest is currently directed to the boundary layer noise source and its impact on interior noise[35]. This has driven the development of feedback control algorithms and sensoriactuator transducers[36] that provide simultaneous excitation and sensing from the same transducer.

The direction of the in-house research under Aircraft Morphing is to more fully integrate the control elements with the structure. Specifically, a program to integrate active vibration control transducers (both sensors and actuators) into the load path of a multi-degree of freedom engine isolation mount is underway. If successful, this will provide a concept for a product that is fail-safe and may be bolted directly into an application such as an engine or transmission mount system.

Current designs for high speed aircraft incur a significant weight penalty to maintain structural integrity in the presence of intense supersonic flow fields such as that from the propulsion system of current SST designs. A second approach[37] will be to embed shape memory alloy wires into composite structures in order to provide enhanced stiffness or damping over a range of aircraft operating conditions. Previous work has demonstrated the ability of such a composite to significantly alter panel properties[38]. This approach will tailor the material properties to utilize the natural heating that occurs due to operating conditions in order to effect control.

Controls The controls work contributes in the mathematical modeling, state estimation and adaptive feedback control for the Aircraft Morphing program. Kalman estimation filters will be extended and applied to the flow control applications. These filters will be developed with the help of researchers with experience with state estimation[39] and control law design for various complex systems[40-41]. New adaptive-predictive controllers will learn the system response on-line and accommodate changes in system dynamics[42], control surface failures and other unknown structural or sensor failures in real-time[43]. These adaptive predictive controllers will leverage state-of-the-art predictive dead-beat[44] estimators.

Models of the flow field will be used to identify the optimal location for control surface components as well as provide computational fluid dynamic (CFD) derived stability and control derivatives. Producing stability and control derivatives using CFD will significantly expedite the generation of mathematical models used in active feedback flight controls for Morphing aircraft systems[45].

The controls work will also leverage the real-time identification mathematical tools[46] for optimal control of acoustical systems. Both adaptive-predictive controllers and optimal control tools will attenuate perceived noise levels on-line. Significant progress has already been accomplished with the adaptive predictive controllers[47]. Additional developments in robustness and performance will be achieved with adaptive optimal controllers and the identified maximum singular value of the return difference matrix. Active and/or passive feedback control systems will be developed for aeroservoelastic systems[48]. Distributed piezoelectric actuation systems, distributed state monitoring systems, and optimal control with novel flow field Kalman estimation represent significant advances in component technologies. When combined they will serve to suppress flutter and stiffen lightweight flexible wings.

Integration The integration effort in Aircraft Morphing has work focused in four areas: embedded components, devices, communications, and mechatronics. In the embedded components work the concepts and technology to embed piezoceramics will be developed[49]. This work will start with the piezoceramic wafer that will first be embedded into a patch. This patch will be a composite lay-up with fiber glass sandwiching the piezoceramic. Electrical leads will be attached to an embedded electrical drive system.

Concepts for flow control devices will consist of an actuator, sensor, drive electronics, and power and communications interfaces. Separate actuator and sensor modules will later integrate into a single device[50]. Ultimately these devices will integrate multiple actuators. In the communications, electronics, and power effort, concepts for a bus architecture will address many more devices than can currently be supported. A bus will include communications to a large number of devices with power distribution to miniature, modular drive electronics. In the mechatronics work, concepts for testing, characterizing, and modeling integrated electroactive materials, such as piezoceramics, will be developed. The purpose will be to develop the capability to control devices and to design devices in less time.

Multidisciplinary Design Optimization Having selected the type of sensor, control law, and actuator, the next crucial step is selecting the number of devices and their locations. The selected locations must optimize some measure of global response, while constraining system requirements. For example in active structural acoustic control (ASAC), the global response is the average sound pressure level in the aircraft cabin while system requirements specify the maximum force available for any actuator. Experience with optimal location of microphone sensors and piezoelectric actuators for ASAC is quite encouraging and highlights the fact that an optimum architecture is hard to pinpoint without an optimization methodology[34]. The Aircraft Morphing program will develop methods for optimal placement of distributed actuators and sensors for aeroelastic control, flow control and acoustic control systems.

n addition to selecting the locations for sensor and actuators, multidisciplinary analysis and optimization can improve the devices themselves. Optimization is especially useful when novel materials and concepts are put forward for actuator and sensor mechanisms. The design of these devices draws together multiple disciplines including materials, structures, fluid mechanics, electronics, and power distribution. The multidisciplinary optimization of a specific device will require close collaboration with the device integrator and analyst. It will then start from existing integrated detailed device simulation and will extract physics-based or generic design-oriented simulations to provide rapid turn-around required for design. A parametric model will relate the device geometry and characteristics to design parameters. The parametric model can be used for numerical optimization or as a planning tool so that the maximum amount of information is retrieved from experimental testing. References 51 and 52 contain further information about the construction and use of parametric models for multidisiciplinary optimization.

The design of a distributed system of actuators and sensors is affected by the uncertainties associated with the physical properties, models and simulation methods used to assess the system. For example, one uncertainty associated with piezoelectric actuator properties comes from the difficulty of bonding the device to a structural member. Other uncertainties come from inexact structural models, approximate aerodynamic simulation of loading conditions and deviations from the expected cruise conditions. These and other uncertain parameters will result in uncertainty regarding the in-flight performance of the device and will propagate to the overall system. Such a system must be designed for both performance and robustness so that the resulting design is insensitive to expected variations in actuator and sensor characteristics. References 53 and 54 indicate that tools for probabilistic structural analysis and optimization are becoming available. The challenge is to extend these techniques to multidisciplinary optimization problems.

PROGRAM ORGANIZATION

We are learning the process of how to successfully implement multidisciplinary teams while retaining specific discipline-based areas of expertise. Historically research has occurred in isolated discipline-based activities with little crosstalk between them. We are attempting to more completely integrate work across a range of disciplines while at the same time retaining the benefits of discipline-based research. Figure 3 shows the program organization in a schematic sense.

The primary products of the Aircraft Morphing program align with each of the four program goals, with oversight provided by the program management. These product goals are reflected in the overall goals and plans of the program. This is represented by the vertical columns in Figure 3.

On the other hand, the technology inputs to each of these sub-elements is discipline based. Each of the discipline efforts is managed separately and is represented by the horizontal bars in Figure 3. Early in our planning process we realized that a specific line of research (for example, high displacement piezoelectric devices) would have impact across a range of program objectives. It is neither practical nor desirable to have a single researcher report to multiple individual program subelements. It is substantially more effective to support a single discipline-based activity in a particular discipline and to establish links to the various program goals (designated by the dark overlap areas in Figure 3). Thus the program has a hybrid management structure in which the research activities are managed by discipline but integrated by subelement. This structure has two main advantages: 1) integration at the highest level (that is, top-down program integration) and 2) reduction of fragmentation at the research level (bottom-up technology development).

To facilitate this hybrid structure, an Integrated Product Team (IPT) has been formed to direct and manage the program. The IPT consists of the Program Manager plus one representative from each of the program core disciplines.

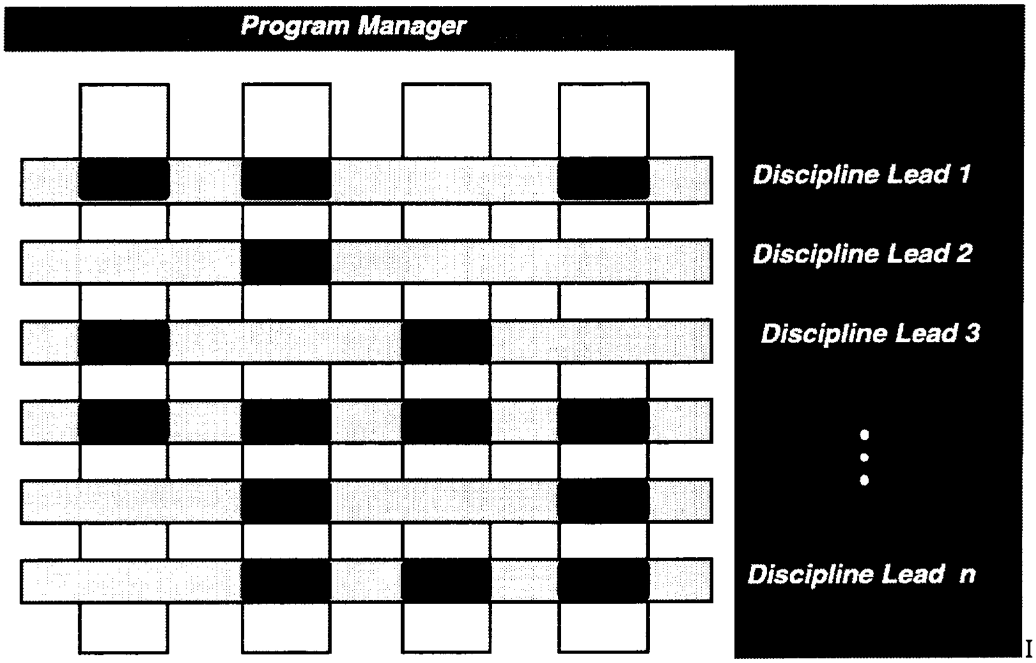

Figure 3. Program hybrid management structure

The IPT has the following roles and responsibilities:

- Technical direction and planning for the overall program
- Coordination and planning of research within each discipline
- Integration of discipline research into program subelements
- Rebalancing of the program on a yearly basis

We have also found it useful to form *ad hoc* working teams to jointly focus at the researcher level in an interdisciplinary manner. For example, we have formed an actuator team, with participants from multiple discipline areas focusing on common requirements and the technology focus required to address those requirements.

CONCLUDING REMARKS

The integration of smart technologies into aircraft systems shows the promise of high benefits if the appropriate technological issues are addressed. The only scenario that effectively approaches the long term issues is one in which efforts across many disciplines are effectively coordinated, that is, an omni-disciplinary (as opposed to a multidisciplinary) effort. This work must be carefully aimed at high payoff applications, not only to justify long term investment in the program, but also to assure the ultimate usability of the technological product of this work. In this paper we have outlined a long-term program that begins to address some of these issues, and which (if successfully completed) has the potential to have major impact on air travel and the way in which aircraft are manufactured and flown.

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