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Biomimetics for NASA Langley Research Center

Year 2000 Report of Findings From a Six-Month Survey

Emilie J. Siochi, John B. Anders, Jr., David E. Cox, Dawn C. Jegley, Robert L. Fox, and Stephen J. Katzberg
Langley Research Center, Hampton, Virginia

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Space Administration

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I. Introduction

Perhaps the most complete chronology of early human attempts at flight is Octave Chanute's *Progress in Flying Machines*, first published in book form in 1894. This work shows the strong influence biological flying creatures had on the first tentative engineering solutions to manned flight. However, it soon became clear that merely duplicating biological morphologies at a larger scale was not a viable solution, and that a new engineering system would have to be devised to carry man aloft. Even though we have long since abandoned natural flight as a guide to aircraft design, the initial inspiration and motivation for flight originated from these early observations and experiments with birds. We now rely on our understanding of the laws of aerodynamics to produce 800,000 pound "birds" that cruise at near the speed of sound (or greater) for thousands of miles nonstop.

Although our engineering designs may exceed nature in some regards, they are inferior to nature in many others. Nature builds systems of staggering complexity, yet these systems provide robust, autonomous, and efficient solutions, which are well-adapted to the environment. Therefore, some are suggesting that the time has come to reexamine nature, in a way reminiscent of those early aerodynamic pioneers, but with an important difference. That is, can biological systems, with their thousands of years of evolutionary re-design, offer fresh inspiration for engineering solutions that work better, are more efficient, and at the same time are more environmentally acceptable to future generations?

This report represents an attempt to see if some of the techniques biological systems use to maximize their efficiency can be applied to the problems NASA faces in aeronautics and space exploration. NASA's interest in examining biological systems stems from long-term agency goals directed toward making aerospace travel and exploration more affordable and efficient, and toward making air transport vehicles safer, cheaper, and more environmentally friendly. Natural systems tend to minimize "cost" for maximum "gain" by exploiting a niche in the environment where they can prosper using some unique capability. They also have the capability of adapting as conditions change (within limits), self-repair (within limits), and cooperative behavior for the good of the group. It is clear that these biological principles can also be applied to engineered systems to minimize cost and maximize gain (function). In fact, we can exploit these concepts even for deep space exploration where biological systems have yet to be discovered.

The biomimetic approach to engineering design is inherently a multi-disciplinary activity that results in a highly integrated, multi-functional system (just like real biological systems). Structures, materials, fluid mechanics, controls, power, sensors, etc. all play multiple and interrelated roles, and any meaningful application of biomimetics to engineering design must combine a number of traditionally separate disciplines. This report attempts to show where Langley's traditional disciplines intersect as biomimetics research methods are applied to the problems we are tasked to solve. Clearly, independent, discipline-specific research will still be required, but the ultimate applications will demand a multi-disciplinary process if we are to successfully mimic natural systems.

II. Definition

Biomimetics is a tool that involves the abstraction of good design from nature. Biomimetics activities are multidisciplinary and engage researchers from the fields of biology, material science, chemistry and engineering, who harness ideas from nature and work together to design new smart materials or structures to perform specific tasks (GE1). An early example of a successful biomimetic material is Velcro, invented by a Belgian named Georges de Mestral, after examining the morphology of plant burrs that were strongly adhered to his dog's hair. Velcro's hooks were copied from nature's design that allows burrs to cling strongly to any fabric surface. Engineers have also been using biomimetics for many years. In attempting to build lightweight structures without sacrificing desirable mechanical properties of materials like steel, engineers turned to fiber reinforced composites. Composites are abundant in nature, both in the plant and animal kingdoms. Trees are made of cellulose fibers in a lignin matrix, shark skin is reinforced by collagen fibers and even the mucus from slime is reinforced by fibers. These examples demonstrate the breadth of problems to which biologically inspired solutions may be applied.

III. LaRC Biomimetics Team

The Biomimetics Team was composed of representatives from five of the six Competencies at LaRC. Team members and their affiliations are shown below:

- Ben Anders – Aerodynamics, Aerothermodynamics and Acoustics Competency
- Dave Cox – Airborne Systems Competency
- Bob Fox – Systems Engineering Competency
- Dawn Jegley – Structures and Materials Competency
- Steve Katzberg – Aerospace Systems Concepts and Analysis Competency
- Mia Siochi – Structures and Materials Competency, Team Lead

The team was formally kicked off on June 22, 1999 with the charter to review the field of biomimetics and identify fruitful areas of research for Langley Research Center which will benefit NASA's customers and the U. S. aerospace industry.

IV. Tasks

The assigned tasks were broadly divided into two sections:

A. The first task was to evaluate biomimetics technology, including what's been done, who the leaders are, what their expertise is and what the growth areas are.

B. The second task was to develop options for LaRC activities in biomimetics including topics for study, needed skills, needed facilities, needed funding and potential alliances.

V. Strategy

Realizing the breadth of ongoing biomimetics activities, the team's strategy for covering the wealth of information available consisted of doing both an external and an internal survey. The purpose of the external survey was to determine what work has been done, who is doing the work and what are the gaps in the field that LaRC may be able to fill. The internal survey was an inventory across Competencies to determine what biomimetic work is already being done on Center, what skills, facilities and other in-house resources that can be considered enabling for biomimetics technology are available. This information gathering task was divided according to the expertise of the team. The areas covered were Materials (Mia Siochi), Structures (Dawn Jegley), Controls (Dave Cox), Aerodynamics (Ben Anders), Systems Engineering (Bob Fox) and Systems Analysis (Steve Katzberg).

It did not take long to discover that over the past twenty-five years, biomimetics activities have taken root in a broad range of disciplines. Due to the volume of information available, it was determined that the most efficient way to educate the team was to invite experts in the area as consultants for the team.

Upon completion of the three-pronged information gathering exercise, the second task was tackled by conducting brainstorming sessions with various groups in each team member's area of expertise. The ideas were fleshed out and are included in this report as the team's recommendations for biomimetics activities.

VI. Internal Survey Results

The purpose of the internal survey was to assess the Center's ability to direct its resources into biomimetics in the near future. As such, the results of the survey contain ongoing work that are either biomimetic or are biomimetic enabling. Biomimetic enabling technologies include research into the development of miniaturized electronic components and nanotechnology, the maturity of which will be crucial for the success of biomimetically engineered systems. The team also noted biomimetics research work completed in the past or biomimetic enabling technology if the skills and facilities used to accomplish past work are still intact and may be revived and directed toward new efforts in biomimetics.

A. Materials – Mia Siochi

The internal survey in the Materials area covers work performed in the Advanced Materials and Processing Branch (AMPB), the Metals and Thermal Structures Branch (MTSB) and the Nondestructive Evaluation Sciences Branch (NESB).

Smart Materials is one of the ongoing programs at Langley Research Center. The largest, coordinated effort in Smart Materials at AMPB is the development of piezoelectric polymers for the Adaptive Vehicle Technologies Program (AVTP). Over the past few years, research has led into the development of some novel polyimides with promising high temperature piezoelectric responses suitable for sensor applications (MI1,MI2). The development of high temperature electroactive polymers in AMPB now includes not only continuing work in piezoelectric materials, but also the initiation of efforts in the development of new electrostrictive materials. Facilities are also available for the fabrication of continuous ferroelectric thin films that have been used to coat micromachined silicon substrates purchased elsewhere.

In order to miniaturize electronic circuits for use in adaptive vehicles, there is ongoing research to develop flexible multilayer circuits and cables using thin polyimide films. Potential applications for these circuits and cables include substrates for chips on boards or chips on structures that can be packaged in constrained areas for data, control and electrical systems in ground based or space flight applications.

Newly funded work from the AVTP involves the development of organic/inorganic hybrids that mimic bone. The objective is to bind organic microspheres with an inorganic binder to create porous, but thermally stable lightweight structural systems. The plan includes embedding sensors into these structures for in-situ health monitoring, temperature sensing and cryopumping response.

The materials expertise in AMPB have been harnessed in collaborative efforts with NASA-JPL for the development of ionic polymer/metal composites (IPMC) as biomimetic sensors, actuators and artificial muscles for planetary applications. IPMC strips were found to be superior to existing motion sensors and micro-sensors. Their vibrational characteristics and unique cryogenic properties can lead to potential applications such as swimming robotic structures, flapping wing machines and various robotic devices with wide ranging utility (MI3-MI5).

In-house expertise also exists in the development of metal matrix composites (MMC). Research on fabrication, joining, and characterization of continuously reinforced titanium was performed at LaRC more than ten years ago in the National Aerospace Plane (NASP) and generic hypersonic programs (MI6-MI9). Work has also been performed on discontinuously reinforced alloys (MI10). Significant experience and infrastructure for performing world-class research on MMCs still exists for fabricating, designing, joining, and characterizing MMCs, and work is being proposed to renew research in the field of MMCs for cryotanks and launch vehicle applications. MMCs take advantage of high strength ceramic fibers in a compliant metal matrix, which is quite similar to the function of ceramic plates connected by proteins in naturally-occurring shell structures.

New research is beginning in the areas of porous metallic structures, also called metal foams, and in freeform laser deposition of metallic powders funded by the Airframe Systems Project Office (ASPO). Naturally occurring structures, such as bones, are highly efficient and lightweight due to selective porosity. Porous metallic structures are being investigated to reduce structural density and provide excellent thermal insulation for high temperature structures such as metallic thermal protection systems for reusable launch vehicles. Laser beams can be used to perform many functions on metals that cells perform within a body; these include new material deposition, flaw detection, flaw repair, and material removal. These tasks are analogous to cellular functions such as proofreading cells checking and correcting DNA strands, phagocytes consuming invading cells, or bones remodeling. This new program funded by the ASPO is investigating processes for depositing metals using lasers to enable the design of complex, multifunctional structures.

Much of the work in the arena of new materials development are in grassroots efforts by individuals or small groups of researchers funded at Director's Discretionary Fund (DDF) levels. As such, these efforts are in rather diverse areas as demonstrated by descriptions of ongoing or past work below.

A recently completed project successfully demonstrated the feasibility of using microwave driven ceramic piezoelectric actuators to eliminate the need for hardwiring actuators on the adaptive surfaces of the Next Generation Space Telescope (NGST) (MI11-MI12).

There is in-house expertise in glass sealants, with previous work involving the development of moisture resistant borate glass sealants for carbon-carbon composite oxidation protection (MI13). This knowledge can be directed to the development of self-assembling structures via sol-gel methods; self-assembly is rampant in nature as a mechanism for replication.

Newly funded work include the development of ionomeric high temperature polymers. This DDF aims to apply in-house expertise in high performance polymers, to the development of new materials with potential applications ranging from self-healing thin films for protective surfaces to matrices for self-repairing composite structures, as well as usage in fuel cells.

The emerging field of Nanotechnology has spurred some work in this area. Interest is focused on improving the properties of existing high performance materials by incorporating nanostructures in various ways. Nanosized organoclays are being chemically modified for incorporation into high temperature polymers used as composite matrix resins. The objective of this work is to develop easily processable resins with reduced permeability for gases such as oxygen and hydrogen which are used as cryofuels. These modified resins could be used to fabricate improved composite cryofuel tanks. Potential improvements to high temperature polymers as a result of the incorporation of organoclays include increased mechanical properties, higher heat distortion temperatures leading to increased use temperatures, and improved radiation and tear resistance of thin films.

As part of a Cross-Enterprise Technology Development (CETDP) effort, there is funded research activity on the chemical modification and incorporation of carbon nanotubes into organic polymers as a possible means of getting sufficient electrical conductivity to dissipate static charge. This must be accomplished without degradation of optical properties (i.e. solar absorptivity, thermal emittance) in order for these materials to be useful in certain space applications. Along these lines, a small effort has been initiated to screen blends of polyimides with carbon nanotubes to investigate potential improvements in the thermal conductivity of films without sacrificing the superior mechanical and thermal properties of these materials.

Another CETDP study aims to synthesize polymers that dynamically change their refractive index and index grating in response to external stimuli such as electrical potential, thermal energy and/or magnetic fields. These coatings can be fabricated into working devices and sensors to create solid-state autofocusing systems that will eliminate moving components in optical devices. It is envisioned that such a system can self-correct for myopia and astigmatism that can occur during a mission lifetime. Development of these photorefractive polymers may have significant impact on telecommunications and computer/data storage industries as well.

Aside from new materials development, expertise on sensor development also exists in the Competency. NESB has long been a leader in non-destructive evaluation. The expertise of the branch lies in the development of fiber optic sensors for in-situ structural health monitoring, non-destructive detection and characterization of structural flaws such as cracks and corrosion in critical structures and complex structural components (MI14-MI20). These sensors are also used for nondestructuve materials characterization such as assessment of material level flaws like voids, inclusions, fiber misalignments and delaminations required for performance and life prediction. Non-intrusive sensors are used for manufacturing process control to monitor and control critical physical and chemical parameters in the fabrication of high quality products (MI21),

Finally, there is a group of researchers involved in the Computational Materials effort aimed at providing an advanced concept for the design of fiber reinforced resin matrix composite. Their approach uses an integrated predictive computer model that bridges the microscopic and macroscopic descriptions of these materials to reduce development costs. The advanced concept under development is aligned with technologies that need to be available in order to fulfill the vision of self-evolving biomimetic systems. Work in progress includes investigation of the influence of molecular weight on the mechanical performance of a thermoplastic glassy polyimide (MI22), molecular simulations of imidization and interfacial phenomena (MI23), molecular modeling of piezoelectric polyimide poling (MI24), and studies of the effects of physical aging on composite properties (MI25).

It is clear from the brief descriptions of both past and ongoing work above, that the Center possesses the necessary skills and facilities to embark on biomimetic activities in the Materials area. The resources available range from the ability to work at the fundamental level using computational tools to the synthesis, characterization and processing of new materials for incorporation into large systems.

B. Structures - Dawn Jegley

The Center’s strength in Structures research can be classified into three major areas:

1. Composites development including manufacturing and applications to large structures (trees are taller than any aircraft)
2. Smart Structures
3. Robotics

When research began into the use of fibrous composite materials, tree structures were examined because they contain long stiff fibers (a series of tubular cells) surrounded by a binding glue substance (lignin). References to the Forest Products Laboratory were quite common in the early papers on fibrous composites, so, in a sense, all research in fibrous composite structures can be considered biomimetic since it mimics the structures of trees. By taking advantage of scaling and tailoring techniques, composite structures can be optimized to support loads of a specific type, resulting in a more efficient, lightweight structure. Over the years, much research has been done using graphite and Kevlar fibers in matrices of resin systems ranging from commercially available brittle systems like 3501-6 epoxy used in the Advanced Subsonic Transport (AST) program, to tougher PETI-5 which was developed at Langley for the High Speed Research (HSR) program. The goals of these recent programs included developing the enabling technologies necessary to build these aircrafts, reducing structural weight (and thereby operating costs and emissions) and reducing manufacturing costs to make these aircraft viable in a commercial market.

Research to improve the design of composite structures is continuing in manufacturing, analysis, and testing. Manufacturing efforts include finding new ways to position fibers to minimize discontinuities and interruptions in load paths, and to minimize failures due to minor damage or delaminations. Improvements could be made by examining the micro construction of natural structures and applying these to man-made structures. Research work has concentrated on tailoring fiber orientation to the anticipated loading and making resin systems less brittle, with less emphasis on improving the fibers themselves or tailoring them locally to improve structural efficiency. Work in this area can be expanded into investigating the way bones and trees avoid failing through holes by avoiding stress concentrations. These efforts can improve the structural efficiency of aircraft and spacecraft, making them lighter and more fuel efficient.

Sandwich structures are also found in nature. For example the human skull is a sandwich structure with a hard outer surface and a soft core. Work in sandwich structures using a variety of materials date back many years and is part of current programs like the X37, where testing of a sandwich structure wing is planned toward the end of 2000.

Through-the-thickness reinforcement using stitching was explored under the AST program and testing of this concept is ongoing. This concept mimics through-the-thickness fibers in some shells and is beneficial in minimizing the propagation of damage. In the AST program, stitched material was found to reduce weight, cost of manufacture and damage propagation in thick structures such as aircraft wings. This concept has been chosen as the baseline structural concept for the blended wing body program.

A new project started in FY '00 involves integrated active controls and tailoring of structures. This can be accomplished by mimicking bones which must carry load. Leg bones, must support the weight of the animal under both static and dynamic loading. Active control with feedback systems can permit fine control not possible with conventional aircraft. Birds can use their wingtip feathers to optimize their flight to minimize energy usage and improve maneuverability. The same things can be achieved in aircraft if an appropriately detailed system is developed.

Programs combining aeroelasticity and control systems have been in existence at LaRC for more than 10 years. Several projects relating aeroelasticity and controls are ongoing. Aircraft wing adaptability to changing flight conditions is being explored by incorporating sensors and actuators on the surface or embedding them within the structure. Inspired by birds and insects who use their wings in complex ways like rotating the wing, flexing the tip, and subtly changing the camber, researchers are aiming for multifunctionality that allows the same structure to maneuver very efficiently in all realms of flight, in ways not currently achieved by mammade flight vehicles.

Forward looking programs involving the incorporation of torque tubes down the center of the wing to allow rotation, incorporation of control surfaces into the structure for smoother wings and modification of wing stiffness by allowing spar rotation, all aim to build more biologically representative wings. The success of these programs depends upon the development of sensors and actuators compatible with these goals. Studies of the effects of embedded sensors on material properties are ongoing to help evaluate the advantages and drawbacks of these types of "smart structures."

The Smart Wing project is part of the Aircraft Morphing Program and has been in place for several years. In this program new smart materials are used to twist and bend airplane wings during flight to morph the aircraft shape into one that is optimal for different flight conditions. Several smart concepts are being studied in this program. The first concept uses tubes of shape memory alloy material to twist the wing from root to tip. When these tubes are actuated, the flexible wing structure twists along its span. This action increases the angle of the tip of the wing, thereby increasing the lift force on the wing. The tubes twisted the wing 1.25 degrees and increased the ability of an aircraft to roll by 8%. The structure is designed so that when the torque tube cools, the wing returns to its previous shape. The second concept is allowing shape memory alloy (SMA) wires or tendons to be stretched, and then embedded in the top and bottom surfaces of a flap. When electric current is applied to the tendons on the bottom of the wing, those tendons shrink and bend the surface downward. Electric current applied to the SMA tendons on the top of the wing bend the surface upward. The system is designed so that if power is not applied, the flap remains in a neutral, or undeflected configuration. Tests of the hingeless surface showed an 8% increase in lift over conventional wings.

The Smart Wing project is jointly supported by the Defense Advanced Research Projects Agency (DARPA), NASA Langley Research Center, Air Force Wright Laboratories, and the Naval Research Laboratories. DARPA funding supports the prime contractor, Northrop-Grumman and subcontractors including Lockheed Martin Astronautics, several universities and small companies. Two 16%-scale F-18 E/F wing models with embedded smart structures were built and wind-tunnel tested in the NASA Langley 16-foot Transonic Dynamic Tunnel.

The Langley Adaptive Aero Demonstrator (LAAD) is getting started now and could provide a unique framework for testing concepts developed under a biomimetics program. The LAAD is a testbed for demonstrating adaptive aeroelastic concepts and evaluating concepts beyond the piezos used today. The goal of the LAAD is to demonstrate LaRC smart structures technology through wind-tunnel testing using a multidisciplinary, integrated approach. This testbed is necessary because while individual smart technologies have been tested at LaRC, a fully-integrated smart structures demonstrator (using in-house technologies) has not previously been designed and tested. Very few examples of such demonstrations exist worldwide.

Another application of smart structures is to suppress vibration by using sensors and feedback. A biological system adapts to changing environments to avoid damage and smart structures can do the same thing. This work is a joint NASA-DOD project. The plan is to team with other agencies to develop flight vehicle structures that can sense their operating environments, process the resulting information, and respond to these stimuli by deforming or deflecting the structure in order to accomplish a mission. The goal is to develop techniques to enhance vehicle performance and eliminate structural dynamic problems, while addressing Technology Development Approach (TDA) goals and Air Force deficiencies. Ultimately this work will reduce vehicle cost, weight, drag, and signature while increasing fatigue life and improving performance.

Other areas of work in the recent past include robotics for space applications which can learn through practice. Work in this area includes developing several techniques such as integral-control based learning, improved learning with compensator, and phase cancellation based learning. These techniques have been implemented and demonstrated through robot training with results including improved robot tracking accuracy by a factor of 100 after practicing eight times and sophisticated learning process improving robot tracking accuracy by a factor of 1000 after practicing twelve times. Animals must adapt to their environment and learn through experience. Robots which cannot be reprogrammed quickly or easily, such as those on space missions, also need this capability to avoid failures due to lack of quick communication with Earth.

A project proposed jointly by MSFC and LaRC but which was not funded this year, was to build ultra-lightweight structures such as space antennae using replicated intelligent colony structures which mimic the techniques coral uses to build reefs. Miniature robots would ‘walk’ along the structure and plant themselves in a preprogrammed location to build the antennae to the correct location.

Precision trajectory robot tracking is another area in which Langley has skills which would enable the development of biomimetic systems. A system with 7-degrees-of-freedom was developed, resulting in a high degree of dynamic coupling with maximum nonlinear effect and 60 dB error reduction in 30 deg/sec tracking with 6 learning repetitions. Biological systems have an excellent ability to position themselves and other objects. This skill would be useful in controlling air and space crafts.

The development of one or more self-propelled, biomimetic microrobotic flying devices was proposed. These avian devices will utilize small-scale flapping wings to produce lift and thrust. Actuator-wings will be constructed using processes recently developed for manufacturing NASA LaRC Macro-fiber composite piezoceramic actuators of dynamically tailored devices. The devices will also incorporate regenerative power systems to allow extended duration operation. The proposal aimed to design, fabricate and test this microavian flapping wing vehicle to demonstrate autonomous flight. If successful, the biomimetic avian device may be used for planetary exploration, military reconnaissance, crop and forest management, and pollution monitoring.

The Structures work described above demonstrates the Center's expertise not only in the modeling and construction of structures, but also in our ability to develop various ways of controlling the structure's maneuverability and efficiency. Key publications summarizing some of the work described are given in the Structures Internal Survey Reference section (SI1-SI10).

C. Guidance and Controls – Dave Cox

In the area of Guidance and Control several projects and past research efforts within the Airborne Systems Competency have followed methods which could be considered biomimetic. Neural networks are probably the most widespread example of this history. Neural networks are inspired by the dense collection of interconnected neurons which comprise human and animal brains. A similar parallel collection of signal paths can be realized electronically in hardware, albeit typically in a more structured arrangement. In practice, most applications rely on a software implementation which allows for easy reconfiguration. Although the biological analogy is clear, neural nets have reached a point of maturity through the refinement of mathematically tractable forms, rather than through a detailed imitation of nature. Therefore, although the processing capability of the brain remains somewhat a mystery, neural networks are well understood and software which expedites their application exists.

In the Guidance and Controls Branch (GCB) neural nets have been applied in the development of new spacecraft design and analysis software in support of the NextGrade Program (CI1). The effects of spacecraft parameter changes, such as the location of reaction wheels or stiffness of critical structural members, affect the overall stability and pointing performance of a satellite. These variations can be predicted in detail through finite element analysis and time-domain simulation, however, this process is time consuming. Given a representative set of parameter changes and the associated effects, neural networks can be trained to recognize the collective and coupled effects of many design parameters, and therefore can provide rapid estimation of performance to help an engineer quickly work through possible design modifications.

Another area where neural networks have been applied is in the development of feedback controllers for non-linear and poorly modeled systems. Work was done in the Dynamics and Controls Branch (DCB), which took advantage of the ability of neural nets to adaptively approximate non-linear functions (CI2). Under DDF funding, and later with support from the HSR program, a series of experiments were conducted which demonstrated the ability of neural networks to control non-linear and unstable plants. The extension of this work to the control of high performance aircraft was also investigated.

Central to the design of many guidance and control laws is numerical optimization, and here too, biologically inspired methods have made some progress. Genetic algorithms are computational procedures which seek solutions to a problem similar to the way natural selection and evolution seek to help a species survive and exploit changing environments. In genetic algorithms the space of all possible solutions is first represented as possible variations in a gnome, represented as a digital sequence.

Mutation is implemented as the random switching of individual genes, and crossover as the mixing of two sets of genes to produce a unique but similar offspring. The algorithm proceeds by evaluating the fitness of each individual, and only allowing the best to survive. Continual "breeding" produces a full population of solution candidates from this set of survivors.

Genetic algorithms are most beneficial in problems for which smooth or mathematically tractable objectives do not exist. In GCB these methods have been applied to determine the optimum distribution of a constellation of low-earth orbit satellites and for refinement of physical parameters in a system design.

There is additional work in the Airborne Systems Competency which has followed a biomimetic path. In the Sensor Research Branch (SRB) a significant effort has been put into development of image processing techniques which improve the color-contrast of images (CI3). The inspiration and direction for this work came from a study of how humans perceive images under varied lighting conditions, as opposed to how a digital camera or film record them. The intrinsic processing of living visual systems is emulated in a processing technique called Retinex, developed by SRB. Retinex is now finding application both within and outside of the aerospace community.

Vision systems need to process large amounts of data, which overwhelm a direct approach. Yet, even simple insects exhibit complex responses to visual information. Work was performed in the Systems Integration Branch (SIB) in machine vision systems, with applications to automated inspection of Space Shuttle tiles. These systems used tools like neural networks to process the images and provide workspace information to a robotic controller.

Finally, work in the Crew Vehicle Integration Branch (CVIB) has had a biomimetic flavor. The focus here is on the consideration of human-factors effects in the design of cockpit display systems. A design methodology called WINGS has been developed, which advocates a pilot-centric view of the interface, rather than the current detailed and visually dense cockpit system (CI4). The result is, in principle, an airplane which makes flying seem natural for the pilot and can be learned at an intuitive level, rather than from an understanding of the aerodynamics and control surfaces involved.

D. Aerodynamics – Ben Anders

The Functional Statement of the Aerodynamics, Aerothermodynamics, and Acoustic Competency indicates that the role of this research group is "to perform theoretical, computational, and experimental investigations in the areas of aerodynamics, aerothermodynamics, acoustics, and hypersonic propulsion, to develop a comprehensive suite of technologies necessary for future high-performance, economically viable, and/or environmentally compatible transport and military aircraft, rotorcraft, missiles, and aerospace launch vehicles and planetary entry systems". The areas of expertise include:

1. Development, assessment, and application of aerodynamic and component integration technologies to enable development of advanced subsonic, supersonic, and high-performance aircraft

2. Development, assessment, and application of acoustic technologies in the development of advanced aerospace systems and to meet environmental requirements

3. Development, assessment, and application of aerothermodynamic technologies to enable development of hypersonic aircraft, launch vehicles, and planetary/earth entry systems

4. Development, assessment, and application of testing technologies to enable aerospace research through testing and experimentation in ground facilities

5. Management and operation of aerodynamic, aerothermodynamic, acoustic, and hypersonic propulsion facilities for testing a broad class of aerospace vehicles

Key skills emphasized for the future include:

1. Unsteady, 3-D aerodynamics

2. Sensor/actuator/control technology

3. Non-traditional computational methods

4. Higher level physical and chemical modeling

5. Unsteady, fully-coupled fluid/structural/acoustic interactions

6. Smart structures for noise reduction

7. First principle-based noise prediction capability

8. Integrated CFD/experimental tools for rapid design/assessment

9. Flow phenomenon-based testing

10. Micro/nano sensors and measurement systems

11. Multidisciplinary analysis

The Competency is composed of 15 branches total, seven of which work in the areas of aerodynamics, aeroacoustics, and measurement technology. Two branches are concerned with aerothermodynamics and hypersonic airbreathing propulsion, while the remaining six branches provide operational support for the major wind tunnels as well as support for data acquisition, model systems, instrumentation, and various other functions related to experimental testing.

Given this rather large playing field, the broad areas of expertise present, and the particular skills listed for future focus, it is clear that the principal ingredients needed for a biomimetic approach to research already exist within the Competency. In fact, as far back as the early 1980s one branch within the competency (the former Viscous Flow Branch) was using a biomimetic approach to find ways to reduce drag by examining the morphologies of fish, sharks, whales, shellfish, and birds. This research culminated with the development of a micro-grooved surface (riblets) that reduced turbulent skin friction drag by 4%-6% on aerodynamic and hydrodynamic vehicles. Micro-groove drag reduction was also found to appear in nature on certain fast sharks where the natural groove scaling (depth/spacing) exactly matched the scaling found to be most effective in the wind tunnel experiments. A host of other drag reduction techniques thought to be used by biological creatures were investigated by this group including compliant walls, grooved afterbodies, fillets, and serrated trailing edges. Bushnell (AI1) and Wilkinson (AI2) give reviews of this Langley work, and Bushnell and Hefner provide a complete overview of turbulent drag reduction work in reference AI3. While this research activity at Langley is no longer active, a number of interesting morphologies were never completely examined. Examples include leading edge bumps (whales, hammerhead sharks), bluff body grooves (shellfish), shark tips and shark fillets for induced drag reduction. The expertise and required facilities for this type of research still exist, and a revitalization of this area could begin quickly. The original drag reduction studies done by NASA Langley's Viscous Flow Branch during the 70s and 80s still stand as an excellent example of biomimetic research, and this work essentially marked the beginning of the field of turbulent drag reduction.

A review of the internal biomimetic research would not be complete without some mention of the pioneering studies of Clarence Cone at Langley in the early sixties. Cone published work on induced drag reduction for non-planer wings, including branched wing-tip designs apparently based on the wings of soaring birds (AI4). This work was followed by a study of soaring performance for sailplanes (AI5) that clearly pointed out how the soaring birds increase their effective aspect ratio by extending their tip feathers. Cone points out that, theoretically, a branched wing tip can have 25% less induced drag than a flat elliptical wing of equal span and lift. This early research probably marks Langley's first serious contribution to biomimetics.

In September of 1999 an informal survey of the AAAC was conducted to determine what, if any, active research programs were using biomimetics as an aid to innovation. The survey revealed that while there is no explicit use of biomimetics in any of the AAA competency research areas (with one exception to be mentioned later), several projects were found to lend themselves well to a biomimetic approach, or could support biomimetic ideas in other areas. For example, sensors and actuators for aerodynamic/acoustic control are clearly used by biological systems such as owls and bats. Owls control flow separation on the upper surface of their wings when at high angle of attack by means of leading edge combs and popup feathers that enhance lift and reduce noise. Downy upper surface feathers and trailing edge fringe also contribute to their low noise flight. Bats have not only an on-board sonar system to locate prey, but they also have the aerobatic agility required to capture that prey. At least part of this agility comes from their ability to alter the camber of their wings in flight and to deploy a leading edge flap. Certain insects (fruit fly, *drosophila melanogaster*) have some flight muscles controlled directly by an inertial sensor (haltere), essentially bypassing (and offloading) their central nervous system (AE1). Since flow control and sensor/actuator development is an active research area within the AAAC (e.g., MEMS, piezoelectric actuators, shape memory alloys for noise reduction, integrated aerodynamic/acoustic design) it seems natural that the above biological examples should be examined for possible engineering solutions to problems of interest.

Similarly, Competency expertise in CFD could be applied to the aerodynamics of insect and bird flight in order to improve our understanding of how these creatures use unsteady lift to improve performance. Again, the goal would be to develop innovative engineering solutions to the problems of flow control on aerodynamic vehicles. This work would build on the current unsteady aerodynamic CFD capability (noise generation, store separation, etc.) and enhance skills already identified as important to the future direction of the Competency. Previous work in the competency on fuzzy logic could also be incorporated to design innovative biologic-like engineering systems.

The single example of an ongoing biomimetic project within the competency is a new effort underway in cooperation with the Airborne Systems Competency. This project involves an experimental study of the dynamics and control of an ornithopter, and includes elements of structures, materials, sensors, controls, and aerodynamics. The interdisciplinary nature of this work is typical of biomimetic research. Again, the most important result of this work may be not so much an ornithopter as a set of skills that can be applied to a variety of engineering problems.

To summarize, the AAA Competency has ongoing research in the areas of sensors, actuators, active and passive flow control, unsteady CFD, and drag reduction that can all potentially benefit from a biomimetic approach. Recently, Anders (AI6) published a review article on biomimetic flow control that suggests that a number of research areas may benefit from the examination of natural flying/swimming systems, potentially producing innovative solutions for the next generation of airborne vehicles.

E. Systems Engineering – Bob Fox

The Organizational Purpose Statement of the Systems Engineering Competency (SEC) states that SEC will "Provide systems engineering, fabrication, facility maintenance, and information services that enable Agency programs/projects and Center Competencies to meet commitments".

Areas of expertise include (from Langley Management System (LMS)):

1. Information Systems
2. Electro-optic Systems
3. Sensor and Actuator Systems
4. Mechanical Systems
5. Facility Systems
6. Flight Vehicle Systems
7. Fabrication Processes
8. Environmental Testing

Within the twenty two branches and four offices of SEC exist a diverse work force and the facilities needed to support biomimetics activities at Langley Research Center (LaRC). During the 1970s two branches in SEC developed an electrically stimulated microelectronics system to promote bone growth. Studies performed at a number of universities demonstrated that an electrical current flow existed across broken or fractured bones. The SEC developed system was successfully tested at the University of North Carolina. It decreased healing time for fractured bones from six weeks to seven days. In the1980s, one branch in SEC and its partner developed a process for slip casting ceramic models. The method can be modified to allow for the fabrication of variable density ceramic components that emulate bone structure. SEC supported the AAA competency in the 1980s in the development of a process for machining micro-grooves (riblets) on aero structures for drag reduction. In the 1990s, SEC developed a beacon identification system that enabled the Air Force to identify friendly sites during air strikes. The SEC developed system transmitted rotational infrared (IR) energy at a specific wavelength which is detected by IR sensors onboard Air Force fighter planes. In nature, insects possess IR type sensors.

A recent survey of SEC biomimetic work uncovered a biology related project. The commercialization office is developing a partnership with Harvard Dental School to investigate why it takes the human body a long period of time to accept dental implants. In some cases the implants are never accepted. It's our theory, that the implants are not compatible with the human system. SEC and its partners have developed and fabricated five dental implants to be tested at Harvard Dental School in 2000.

SEC and its partners are developing, modeling, characterizing and qualifying a number of smart material actuator and sensor technologies for aerospace use. The actuator technologies being developed could potentially be used in biomimetic devices for: underwater propulsion (traveling wave fluidic motors), electric mechanical drive systems for snakes (traveling wave), flapping wing fliers (act as muscles to create motion in wings of birds or bats), shaping of structures (control), controlling structural stiffness (aero dynamic shape), and as the legs of land rovers. Examples of the technologies being characterized for aerospace use are: THUNDER, macro–fiber composites (MFC), shape memory macro fiber composites (SMMFC), and dynamically tailored devices (DTD). Existing agency applications of the technologies include: vibration control of large flexible solar arrays, mirrors and sails, jitter suppression of satellite platforms (JPL-NRO-USAF), electromechanical devices for optical system adjustment and scanning, gossamer structure alignment and vibration dampening, synthetic jets vortex generators with Advanced Aerospace Vehicle Technology program (AAVT) funding in 2000, airfoil shape control (AAVT funding 2000), active rotor control (AAVT funding 2000-ARMY), wing buffet alleviation (NASA-DoD), noise cancellation (LaRC-GRC-BBN) and solid-state motors for the Fourier Transform Spectrometer (FTS) and Gas Aerosol Measurements in Space (GAMS) projects.

THUNDER wafers are prestressed durable devices that double as actuators which produce large out of plane displacement and as sensors that provide high output voltage under strain. MFCs are encapsulated high performance, in-plane, piezoelectric fiber composite strain devices. SMMFCs (under development) are encapsulated high performance, in-plane, shape memory fiber composites strain devices. Technologies are being developed to increase the bandwidth of SMMFCs. Dynamically tailored devices are designed to have a structurally prescribed response and actuation. The dynamically tailored devices use materials such as ferroelectrics, shape memory alloys, active polymers, etc. and are designed to specifically provide either a flat response over an extend frequency range, or an artificially large displacement at a narrow nodal frequency.

Use of THUNDER, MFCs, SMMFCS and DTDs in aerospace applications will require fully integrated light weight systems that can be developed successfully only with cross Competency teaming. Animals, insects and fish are fully integrated biological systems that process information from numerous sensors to make real time decisions. An increased understanding and the mimicking of neural networks can enhance our aerospace project controls (decision making). Fully integrated systems for the previously mentioned applications will require the development of processes utilizing novel LaRC materials for flex cables and circuits, passive devices, radiation shielding, innovative power systems, electrical interconnects, continued sensor and actuator development and the implementation of MEMs technologies. The risk of fully integrated systems has been reduced to some extent by recent advances in these technology areas. Flexible cable development, novel actuator/sensor development, the modeling and characterization of these devices and microelectronics are being funded by the Advanced Aerospace Vehicle Technology (Aircraft Morphing) AAVT program office. Controls, flexible multi layer circuits, chip-on-structure and the FTS motor development were previously funded in 1999 under the Advanced Sensors and Actuators Program (ASAP) by the Space and Atmospheric Science Program Group (SASPG) .

Agency programs/projects and Center competencies have depended on SEC support to meet commitments. Past SEC contributions have reduced the risk and increased the Technology Readiness

Levels of many novel integrated technologies for aerospace. This synergistic relationship has resulted in the development of numerous biomimetic enabling technologies. The existing expertise and knowledge base can be channeled into future biomimetics activities at LaRC.

VII. External Survey Results

The external survey results can be classified into fundamental and applied work. Most of the fundamental work is performed in academe, while the applied work is emphasized in other research institutions such as government labs, research institutes, military research labs and industry. Research performed in academic settings is often narrower in scope and results are easily accessible in the open literature. On the other hand, the nature of the applied work in other research institutions tend to yield more overlap between disciplines, and information on the results of research are less forthcoming. It was logical therefore to organize the findings from the external survey such that research in universities is structured like the internal survey above, while available information from the other sources is combined and organized according to the type of institution where the work is being performed.

A. Materials – Mia Siochi

Biomimetic activities in materials development are focused on the mimicry of materials that plants and animals are constructed with. The literature therefore abounds with work on the development of polymers, ceramics, fibers and hybrids of the above materials. It is recognized that nature does not use the diverse chemistry found in synthetic materials, rather multifunctionality and complexity are achieved by organizing recurrent components into hierarchical structures over large length scales (EM1). Soft biomaterials tend to be made from collagen and cellulose, while hard composites are made of calcium carbonate, calcium phosphates and silica. The robustness and adaptability of biological systems are even more remarkable considering that these properties are imparted by the synthesis of materials in-situ, under aqueous conditions at ambient temperature and atmospheric pressure. In contrast, synthetic high performance materials are typically made under harsher conditions with environmentally hostile solvents, at elevated temperatures and pressures. Although biological systems have to function in much more benign conditions than those which engineering materials are designed for, there is much to be gained by an understanding of how these complex systems come about.

Many groups have delved into the benefits of looking towards biological systems for inspiration. Examination of Russian literature published in the journal *Bionika* from the late ‘60’s to the ‘90s indicate there was interest in the understanding of the morphology of aquatic animal skins such as those of dolphins, sailfish and swordfish (‘69-’89), as well as the chemistry of slimy secretions in fast swimming fish (‘76-’82). The relationship between function and morphology in biological systems was discussed in two books by Wainwright, a zoologist from Duke University who has been a renowned advocate of biomimetics since the early ‘70s (EM2, EM3).

The diversity of applications in which biomimetics can play a significant role is demonstrated by the breadth of work compiled in books on biomimetic polymers (EM4), where much of the earlier efforts in this area focused on enzyme activity as a logical starting point, to expansion into research in biomineralization, biogenic semiconductors, nanostructural fabrication, template directed nucleation and growth, bacterial fibers, organoceramic nanocomposites, artificial membranes, abalone shells and spider silks (EM5, EM6). The development of atomic and molecular wires necessary for biomimetic systems includes research on the self-assembly of metals (EM7). The challenge in looking at complex biological systems for inspiration in solving engineering problems, is that it requires the cooperative efforts of multidisciplinary teams involving engineers, chemists and biologists, a marriage of disciplines where communication can be difficult. Nevertheless, efforts are being made by researchers to improve interdisciplinary interactions. One result of these efforts is documented in reference EM8, which discusses how biologists use nano and microfabrication in their research.

Note that the listing of various research topics above links biomimetics with nanotechnology. Indeed, most biological processes that are required for the synthesis of complex structures begin with cells operating at the nanoscale level. This being so, recent strides made in nanotechnology are critical to biomimetics. It is anticipated that nanotechnology will open doors to the discovery of new materials with unusual properties because the ability to manipulate matter on the nanoscale will allow the tailoring of fundamental properties at the macroscale (ME9). As befitting the multidisciplinary nature of biomimetics, progress made at the nanolevel will have broad impact on twenty-first century materials that span applications in electronics, biomaterials, information technology, telecommunications, transportation, and medicine.

Not surprisingly, since the nanotechnology explosion is near its infancy, the emphasis of most work in this field is the demonstration of the usefulness of nanotechnology and its potential (ME10). The key to revolutionizing the materials world is a fundamental understanding of how things work on this scale, for it is the understanding at the fundamental level that will allow the processing of these new materials into useful products. The characterization tools required for inspecting nanoscale materials are already available; however, we are used to training them at objects that are half an order to an order of magnitude smaller. The Materials expertise available at LaRC can make contributions to fill this gap, by translating our skills and knowledge at the angstrom level to gain a fundamental understanding of the processes that occur at the nanometer level. This fundamental understanding is also essential to the development of biomimetic materials possessing self-healing, self-repairing and multifunctional characteristics common in biological systems.

Academe

Interest in biologically inspired materials is not limited to the United States. A sampling of published literature in this area shows that research is being conducted in England, Japan, China, Finland and Canada among other places. Biomimetic materials activities in universities span a range too broad for complete coverage in this report. This survey is therefore meant to touch on some of the topics relevant to the development of aerospace materials.

Spider silk has been a topic of intense study due to its attractive mechanical properties – its tensile strength is higher than steel's, it's as tough as Kevlar which is used in the manufacture of bullet proof vests, and its extensibility is comparable to rubber. All these properties belong to a material made under ambient conditions by spiders. By gaining an understanding of how spiders produce silk, scientists hope to mimic the manufacturing process at an industrial scale. At Cornell, Jelinsky is using nuclear magnetic resonance (NMR) to probe spider silk morphology. At the University of Wyoming, Lewis is cloning the protein molecules that make up spider silk. Structure/property relationships in spider silk are being elucidated in Gosline's laboratory at the University of British Columbia.

Another biological system that has gotten much attention is nacre, a ceramic/polymer nanocomposite found in mollusk shells. Nacre is a 95/5 composite of calcium carbonate to organic material, yet, its fracture toughness and strength are orders of magnitude higher than that of monolithic calcium carbonate. It is believed that nacre's superior properties are due to the high degree of organization between its components. The understanding of the relationship between its structure and properties is not complete. Leading researchers in this area include Aksay at Princeton University, Sarikaya at the University of Washington, Morse at the University of California, Santa Barbara and Currey at the University of York. Understanding biological organic/inorganic composites is also the goal of Mann at the University of Bath and Calvert at the University of Arizona.

Research on bioadhesives is also relevant to aerospace applications, especially where structural joints have to possess moisture resistance. An example of a well studied bioadhesive is one found in mussels. Much of the work done in this area is by Waite, now at the University of California at Santa Barbara.

Hierarchical structures dominant in natural systems are often assembled without covalent bonding at the nanoscale. Self-assembly of nanostructures is a highly subscribed field of study; systems under investigation range from biopolymers to metals used for atomic wires. Some of the leading researchers in that arena are Lehn at the University of Strasbourg and Whitesides at Harvard. Many universities in Japan are active in this field. Novel supramolecular structures such as those reported by Stupp at Northwestern University have resulted from the widespread interest in this area.

Hierarchical structures are also an important aspect being investigated in bacteria. These creatures are interesting because they have been in existence for longer than any group of organisms, in extreme environments no other living organism can survive (ME11, ME12). Work by Mendelson at the Indiana University shows the potential for synthesizing macrofibers from bacterial cell wall, making bacteria a source of new materials. Magnetotactic bacteria were discovered by Blakemore of the University of New Hampshire in 1975. They orient and navigate along geomagnetic lines due to inorganic particles known as magnetosomes whose "hierarchical structure is a masterpiece of permanent magnet engineering (ME5)." This information may be useful in the development of new materials for navigation sensors.

Scientists are also looking to plants as alternative sources of new materials. For example Glasser at Virginia Tech has been mimicking wood with cellulosic composites (ME13) and in Japan, the reproduction of wood microstructure in ceramics is being investigated (ME14).

Nature provides an endless source of inspiration for new materials. The full potential of the biomimetic approach in new materials development cannot be exploited unless scientists are willing to collaborate in multidisciplinary efforts. Very few groups have successfully done this. One example is a group headed by Daniel Morse at the University of California at Santa Barbara, where an interdisciplinary team composed of faculty and students from Molecular Biology, Chemistry, Physics, Materials, Chemical Engineering and Marine Biology work closely together to understand how mechanisms in nature can be used to produce high performance nanocomposites. The need for training students in multidisciplinary environments is a new paradigm in education. Its importance is recognized and encouraged by groups that have been tasked with charting the future direction of materials research (ME15, ME16).

B. Structures – Dawn Jegley

Many people have studied biomimetics in structures for the past 50 years. Some of that work are described in references SE1-SE12. These studies include a variety of materials and natural systems for comparison. Studies of more specific applications are outlined below.

Academe

The University of Bristol and the University of Florida have incorporated biomimetics in their curriculum in the Mechanical Engineering and Aerospace Engineering Departments, respectively.

The University of Florida has combined structures experts with biomechanical experts to study bones and apply what they learn to both medical applications but also to vehicles. By mimicking the behavior of bones, better bone replacements can be developed; moreover, an understanding of bone behavior and construction can be applied to non-medical systems. Bone growth and fiber placement techniques can be exploited.

Researchers at the Academia Sinica in the People's Republic of China, are studying the structure of bamboo including the helical reinforcement and transition zone with the goal of improving the design of fibrous composite structures (SE13).

The different cross sections of load-carrying bones is being examined at the University of Barcelona to understand how changes in cross section affect the load-carrying ability of the bone in mammals and birds. These differences influence the behavior of the bone structure and can be used to improve the efficiency of structures (SE14).

Birds and dragonflies are being studied to learn about flight mechanics. Wood and shark skin are being examined to learn about composite structures and mollusks are being studied to learn about fracture mechanics at the University of Connecticut (SE15).

The Air Force Office of Scientific Research is funding Worcester Polytechnic Institute and the Air Force Institute of Technology to examine the multifunctionality of most naturally occurring systems. For example, the sharp spines on hedgehogs are used to ward off predators and as a barrier against impact damage when rolling or falling. Multifunctional structures tend to have very complex forms down to the cellular level and those forms can be studied and copied for use in man-made structures. In addition, animals must be adaptable to survive, a trait of few man-made structures, but one that could be of great advantage (SE11-SE12).

Numeric modeling of biological systems is being done at the Doshisha University in Japan. The goal of this study is to analyze and predict the ability of bone structures to absorb impact. The bone marrow consists of open-cell structures filled with a viscous fluid. A honeycomb filled with fluid to disperse compressive load is the translation of this to composite structures (SE16).

The effects of tailoring and scaling were presented at a NASA conference on scaling in composite materials in 1993, by Professor Dick Wilkins of the University of Delaware (SE17). Scaling effects are also being studied at Michigan State University and Duke University.

Smart structures research is ongoing at many universities and government agencies. Much of this research is aimed at military aircraft, but has applications to commercial aircraft and space transportation vehicles as well. Research in smart or adaptive structures is ongoing at Pennsylvania State University, University of Maryland, Michigan State University, University of Michigan, Stanford, University of Stuttgart, MIT, Harvard, North Carolina A&T, North Carolina State University, University of Texas, Auburn University, Virginia Polytechnic and State University and Cranfield University in England. These studies include using piezoelectric sensors and actuators to modify the shape of wings, to suppress vibration, for active control of rotorblades, and to move control surfaces, including using discrete actuators to induce large deflections.

Another area of biomimetics is sensing damage in structures. Ongoing work includes sensing damage in carbon fibrous composites by using electrical resistivity at Cranfield University.

The University of Toronto is using thermal residual stresses to alter buckling and vibration behavior and tailoring of structures.

Creeping, crawling, swimming, flying and walking robots are being built all over the world for selected applications. A few of these are described in the next few paragraphs. Numerous universities have micro-flier programs, including UCLA, the University of Florida, Georgia Tech, Vanderbilt, Stanford and MIT. Georgia Tech is developing a “reciprocating chemical muscle for its micro air vehicles.”

Numerous universities and organizations are examining snake locomotion and building snake-like robots that move like real snakes. Research in building robots with snake-like motion is ongoing at Carnegie-Mellon University, The University of Metz in France, The Swedish Institute of Computer Science, Cal Tech, University of Florida and the Tokyo Institute of Technology. Most of these efforts are funded by DARPA and are aimed at military applications.

Dartmouth is studying robotic inchworms. MIT has programs looking at small crawling robots. MIT is building a swimming robot and Northeastern is building a bionic lobster.

Shape memory alloys are being studied at the University of Michigan, Michigan State and Aerotech.

C. Guidance and Controls – Dave Cox

In performing the external survey for controls related work, the area was extended to include the field of Machine Intelligence, with particular emphasis on examples of autonomy in robotic systems. Although there are lessons to be learned from nature in traditional guidance and control systems, the larger picture for NASA is to achieve a high degree of autonomy in the operation of aerospace vehicles. This involves, not only low-level dynamic control, but also decision making capability, health monitoring, mission planning, and even the ability to build upon scientific data gathered during a mission. The need for autonomy is particularly relevant in the design of deep space and planetary exploration missions, where communication with ground controllers on earth is difficult and involves large latencies.

The idea of machines that could imitate the intelligence of man is not new. Speculation over the possibility of thinking machines dates back to 1842 with Charles Babbage's proposed analytic engine (CE1). In the 1950's the work of computer pioneers Alan Turing and John von Neuman also sought to understand the limitations of a machine’s ability to think (CE2), and the analogues between computer codes and the complexity seen in natural life (CE3).

These topics were controversial in their time and are no less so today. Even with computer capacities exceeding the most optimistic projections, machines that can think and reason are not yet available. The work in artificial intelligence, however, continues aggressively. The current trend is less of the top-down approach based on human reasoning, and more of a bottom-up approach, building from components which when combined will lead to intelligence. Researchers are looking more and more to how biological systems actually function, and how this can be imitated in the design, or the evolution, of thinking computer systems.

Biologically inspired work in this area can be broken into two different but related categories. The first is biologically inspired methods that are general in nature and have application to a wide range of engineering problems. Neural networks, genetic algorithms, fuzzy logic and expert systems all fall into this category. These are the tools that can be used to build up intelligence in the control of aerospace systems, and also have wide application in design and analysis. Research continues in these areas, but the fundamentals are well established and described in graduate level textbooks such as those listed in references (CE4-CE7).

The second category takes more of a system level view, and seeks control systems that make the response of machines closer to the behavior of animals. The field of Artificial Life looks at systems that evolve and adapt within the confines of a digital world. There are striking parallels between the programmed response of independent computer routines and the biological response of very simple organisms like bacteria and viruses (CE8). As the number of interacting agents increases, system behavior becomes complex, but often, patterns of self-organization emerge which result in a macroscopic behavior very different from the underlying individual behavior. The field of Complexity Theory (CE9) looks at this in a very general way, and recent work in multi-agent and swarming systems seeks to apply this complexity to the solutions of real world problems (CE10, CE11).

Academe

A large number of universities have research programs in these areas. Some are based in Computer Science departments, others in Engineering, Biology or even Psychology departments. Many of the successful research groups are at Centers which span multiple departments, and involve professors with different fields of expertise. The following are summaries of research activities at selected universities whose work was most closely aligned with Langley's interest in biomimetics. This list is far from complete, but rather it is intended to be representative of the work being conducted by universities in this area.

1. Computational NeuroEngineering Laboratory, University of Florida, Gainesville.

Director: Jose Carlos Principe

The Computational NeuroEngineering Laboratory (CNEL) is a research collaboration between the ECE Department and the Brain Institute of the University of Florida. The CNEL conducts research in adaptive information processing systems. The research is interdisciplinary and focuses on nonlinear adaptive signal processing, pattern recognition, neuromorphic computation, neurobiologically-inspired models and devices, information theoretic learning and analog computation.

2. Autonomous Agents Research Group, Case Western Reserve University

Director: Randall D. Beer

This group is based in the Computer Science Department and involves collaboration with professors from the Mechanical and Aerospace Engineering Departments and the Department of Biology. The work carefully emulates biological systems, particularly in design of control systems for locomotion in legged robots. Research areas include: evolution of dynamical nervous systems for autonomous agents, dynamics of adaptive behavior in recurrent neural networks and control of locomotion in biologically-inspired robotics.

3. Artificial Intelligence Research Laboratory, Iowa State University

Director: Vasant Honavar

The Artificial Intelligence Research Laboratory works on basic and applied research problems in Artificial Intelligence and Cognitive Science. Research areas include: biological computation, bioinformatics and computational biology, complex adaptive systems, network information systems and applied artificial intelligence.

4. The Artificial Intelligence Laboratory at MIT, Massachusetts Institute of Technology

Director: Rodney Brooks

The MIT Artificial Intelligence Laboratory conducts research in many aspects of intelligence. The lab's aim is two-fold: to understand human intelligence at all levels, including reasoning, perception, language, development, learning, and social levels, and to build useful artifacts based on intelligence. Research areas include: learning and vision, biological and computational learning, mobile robotics, humanoid robotics and cognitive robotics.

D. Aerodynamics – Ben Anders

An external survey of the literature on the biology of flight in both air (aerodynamics) and water (hydrodynamics) has yielded a wide spectrum of interests, activities, and funding agencies. Rather than present a lengthy review of this research area, the following discussion will indicate some of the more important research groups and summarize their contributions to the literature. The work is loosely divided into two groups: (1) biomimetic flight research (understanding and applying biologic results to engineering problems) and (2) biological flight research (work done mainly by biologists for understanding natural flight). A partial list of some of the published literature is given in the bibliography section of this report, and a large collection of links to various national and international web sites are listed on the LaRC Biomimetic Team web site (http://kvass.larc.nasa.gov/biomimetics/ for LaRC internal use).

Biomimetic Flight Research

Much of the current biomimetic flight research is dominated by work performed under U. S. military lab sponsorship (see the section below on Military), but biomimetics research is by no means limited only to the U.S. German research as far back as the mid 1970s looked at novel undulating propulsion techniques similar to that used by dolphins (AE2). The possibility of using insect flight mechanisms on a large scale was examined by De Temple (AE3), and Bechert (AE4) recently reviewed a variety of biological surfaces for drag reduction. Russian work in this area has been difficult to assess, except for numerous articles in the Russian journal *Bionika* on compliant surfaces (dolphins) and fish propulsion (particularly the years 1970 to 1990). John DeLaurier's work at the University of Toronto on ornithopter analysis and design has led to a successful demonstration of a large flying ornithopter where aeroelastic tailoring was incorporated much like bird wings (see the project web site at http://www.utias.toronto.edu/test/res/fm/fda-proj.html#proj2).

University research efforts in biomimetics include robotic fish at MIT, chemical muscles at Georgia Tech, artificial insects at Vanderbilt, and a host of universities working on micro-air vehicles including Stanford University, University of California at Berkeley, University of California at Los Angeles, University of Florida, and University of Southern California. A more complete listing of universities is located on the Biomimetics Team Home Page (http://kvass.larc.nasa.gov/biomimetics/)

Biological Flight Research

The biological flight literature database is extensive, and only a few of the most important examples will be mentioned.

Much of the Russian literature on the form and function of biological locomotion is captured in the journal *Bionika* cited earlier. Grodnitsky (AE5) summarizes much of the known information on insect flight in the book *Form and Function of Insect Wings*. Research in the U.K. on fish locomotion and bird and insect flight is characterized by the work of Lighthill (AE6, AE7), Rayner (AE8), and Ellington (AE9, AE10). In fact, much of our understanding of the fluid mechanics of marine propulsion can be traced back to those early works of Lighthill, especially the survey paper *Hydromechanics of Aquatic Animal Propulsion*, published in 1960, and the monograph *Mathematical Biofluiddynamics*, published in 1975. A representative sampling of the literature in the U. S. on bird and insect flight must include the work of Ken Dial at the University of Montana (AE11-AE13) on the biomechanics of bird flight, Michael Dickinson at the University of California, Berkeley (AE14-AE16) on the aerodynamics and neurological mechanisms of insect flight, and Robert Dudley at the University of Texas, Austin (AE17, AE18) on the aerodynamics, biomechanics, and energetics of insects and hummingbirds. In fact, Dial, Dickinson, and Dudley in the U.S. and Ellington and Rayner in the U.K. are arguably the world leaders in biological flapping flight research. All but Rayner were contacted during the external survey phase, and Dickinson served as a consultant to the team and presented a seminar at Langley. All of these researchers are biologists, and all indicated that computational support for unsteady flows was a critical need. In view of this, it appears clear that partnering with aerodynamicists, especially computational fluid dynamicists would be advantageous. Langley has this skill in-house, and could possibly quickly contribute to the understanding of the aerodynamics of flapping flight by partnering with one or more of these biologists. In addition, the work of Geoffrey Lilley (currently at ICASE on leave from Southampton University) has added significantly to our understanding of the silent flight of owls (AE19), and his expertise could be an invaluable bridge between aerodynamicists and biologists, as well as providing guidance in biomimetic noise reduction studies.

There are a number survey books and articles that should be mentioned. The first is Steven Vogel’s book, *Life in Moving Fluids* (AE20), which is a remarkably readable introduction to biological form and function in air and water. Another is Robert Dudley’s new book, *The Biomechanics of Insect Flight: Form, Function, Evolution* (AE18) from Princeton University Press. In addition, R. J. Templin (AE 21) summarizes the available data on the geometry and flight characteristics of many types of winged animals, and Shyy, et al. (AE 22) provides a through review of biological scaling laws and low Reynolds effects as relevant to micro air vehicles. Finally, a recent popular press book by Janine Benyus entitled *Biomimicry* (AE21) summarizes what is termed the “revolutionary new science” of viewing nature for what we can learn from it, not what we can extract from it. This book provides the reader with a good introduction to the biomimetic concept.

E. Military

Some of the earliest efforts to understand natural biological systems as a guide to improved engineering systems were initiated by the Department of Defense (some Navy work dates back to the late 1950s and some Air Force studies were done in the early 1970s). The Department of Defense has continuing interest in biomimetics and sponsors much of the research at universities. Different military research laboratories continue to participate in biomimetics research activities as well. Some of the ongoing work will be pointed out here, but overviews on most of this DoD-sponsored work can be found at the following web sites:

Defense Advanced Research Projects Agency (DARPA)	http://www.darpa.mil/
Office of Naval Research (ONR)	http://www.onr.navy.mil/
Naval Undersea Weapons Center (NUWC)	http://www.nuwc.navy.mil/
Naval Research Lab (NRL)	http://www.nrl.navy.mil/
Air Force Office of Scientific Research (AFOSR)	http://ecs.rams.com/afosr/
Air Force Research Lab (AFRL)	http://www.de.afrl.af.mil/
Army Research Office (ARO)	http://www.aro.ncren.net/

Strategic research areas outlined by the DoD include biomimetics, nanoscience, smart structures, mobile wireless communications, intelligent systems and compact power sources. While the focus of each branch of the military may be different, some common topics of research among the branches include: sensors, adaptive methods, intelligent agents, machine vision for reconnaissance and surveillance missions, distributed interactive simulation, man-machine interaction, smart structures, biosensors and biocatalysis.

1. Navy

Research in Navy labs focuses on surface ships including carriers and their aircraft and submarines. They lead the work in the development of carbon nanotubes and organic composites for electronic and structural applications. Topics of interest to the Navy are adhesion, surface properties relating to ship antifouling coatings, bioadhesion, novel cooling technologies, energetic materials, enzymatic synthesis of energetic materials, biomimetic catalysis, self-assembled mesostructures, bioluminescence, fast biosensor arrays, cell-based sensing, biomimetic sonar, tactile information processing, sensory-guided motor control, autonomous undersea vehicle/manipulators, neural computation plasticity, and soft/fuzzy logic/neural networks.

Naval Undersea Weapons Center (NUWC)

Novel biomimetic propulsion techniques and hydrodynamic flow control for highly efficient, small-scale, semi-autonomous undersea probes have been of interest at the NUWC.

Naval Research Lab (NRL)

Work on biosensors, self-assembly, and molecular engineering is being sponsored by the Center for Biomolecular Science and Engineering of the NRL.

2. Air Force

Air Force research labs focus on atmospheric and space flight applications. Their interest in lightweight, small devices for airborne platforms led to a program to develop visible laser technology. They have an active program in using optical compensation for imaging of space objects through the atmosphere. Molecular mechanisms of infrared biosensing are also being studied.

Air Force Research Lab (AFRL)

The mission of the smart structures core area is to develop and transition flight vehicle structures which can sense their operating environments, process the resulting information and take action based on that information (Air Vehicles Directorate, AFRL). Animals sense their surroundings and adapt. The goal in applying this research is to improve flight performance. Space Vehicles Directorate researchers are working on MEMS and multifunctional structures. AFRL researchers have made breakthroughs in using neural nets for the design of new materials.

3. Army

Army research work focuses on soldier and land platforms. They have active programs in compact displays and detectors to support combat soldiers and image science for target recognition. Their work also include human cognitive processing, macromolecular structure, function and assembly, nanoscale mechanics, olfactory and integrated multifunctional sensing, and microbial degradation of aromatic compounds

Army Research Lab (ARL)

The Army Research Lab is doing work in active vibration suppression using piezo ceramics and other aspects of smart structures. They have expertise and facilities for rapid prototyping and nanoelectronic prototyping. Current research areas also include robotics and soft computing such as fuzzy logic, neural networks, genetic algorithms and probabilistic reasoning to support projects in machine learning, intelligence and reconnaissance, surveillance and target acquisition technologies. Work is ongoing in the development of smart armors and lightweight materials technologies.

F. Other NASA centers

NASA administrator Dan Goldin's directive to look to the biological sciences for possible solutions to our engineering problems is clearly being considered by the different NASA Centers. A message from Matthew Bold of the Defense Strategies and Systems, Inc. in Centerville, VA was picked up on the January, 1999 archives of the biomimetics discussion list at http://www.mailbase.ac.uk/lists/biomimetics/archive.html indicating that their NASA customer is interested in looking for ways to solve engineering problems biomimetically. Attempts were made by the Biomimetics Team to find out what biomimetic activities other NASA Centers were involved in. Most of the information was gleaned from what's accessible on the Center websites.

1. Ames Research Center (ARC)

In 1991, Ames commisioned a report to look into potential areas of biomimetics research for ARC. A contractor report by Research Triangle Institute documents the literature survey and bionics workshop conducted, as well as recommendations for areas of research for the center (GE2). It appears that the recommendations were not pursued at that time. Recent communications with Lynn Harper, head of the Astrobiology Advanced Missions and Technologies Program, revealed that a group has been put together around the fall of 1999, to look into what role ARC can play in biomimetics.

While there doesn't appear to be a coordinated biomimetics program at ARC, there clearly are biomimetics activities going on already. Ames is the Center of Excellence for information systems and their work includes autonomous diagnostics, autonomous spacecraft navigation and remote task planning for spacecraft and rovers. The "Intelligent Agent" program is their most visible effort; it won the1999 Software of the Year Award. Biological nanotechnology is also a topic of research. They have an activity to synthesize light driven systems using enzymes embedded in membranes.

ARC has a 30 member carbon nanotube centric nanotechnology team. This team has been operating for about 4 years with significant efforts devoted to computational modeling and applications of carbon nanotubes especially in electronic and biomedical applications. They also have research efforts in the development of protein based nanotubes.

2. Jet Propulsion Laboratory (JPL)

In collaboration with Cal Tech and other universities, JPL is using biological computing, robotics (snake robots), telerobotics, microelectronics and nanotechnology for applications in planetary exploration. Under support from the New Millennium Program JPL has have sponsored two workshops investigating the use of "Biomorphic Explorers" (BEES). The work has focused on the definition of mission scenarios for autonomous planetary exploration using small mechanical systems that mimic the mobility and autonomy of natural systems. The workshops involved people from a broad range of disciplines and proceedings from the workshops are available on line at the BEES homepage, http://nmp.jpl.nasa.gov/bees.

3. Glenn Research Center (GRC)

GRC is well equipped for tribology characterization and testing of MEMS devices and can extend this capability to study nanostructures, with the focus being the behavior of nanodevices in harsh environments such as high temperature, pressure and chemicals. They also have over ten years of experience in the development of nanostructured chemical sensors that are now being used as NOx sensors. Ongoing work includes the fabrication of nanotubes with controlled aspect ratios. Expertise exists in the development of nano power sources such as thin film batteries and fuel cell batteries, as well as in the development of power storage devices.

4. Dryden Flight Research Center (DFRC)

As part of the Environment Research Aircraft and Sensor Technology (ERAST) project, Dryden is collaborating with AeroVironment on the development of unmanned air vehicles (UAVs) for weather observation purposes. The goal is to reach 100,000 feet and perform an extreme duration mission of 96 hours over 50,000 feet. Several vehicles are being tested. The Pathfinder Plus is a solar powered UAV with a 100 ft wingspan that holds the altitude record of 80,000 feet. The Altus completed a major milestone of staying at 55,000 feet for over four hours to collect information on solar radiation penetration and reflection in clouds. They continue to improve on the remote piloting capability and "over-the-horizon" communications capability of the multiconfiguration Proteus.

5. Johnson Space Center (JSC)

JSC is the lead center in the production of carbon nanotubes. They are funding the group of Nobel Laureate Richard Smalley at Rice University to develop fabrication methods for high purity carbon nanotubes. Highly pure nanotubes are required to study potential uses of nanotubes.

6. Kennedy Space Center (KSC)

KSC is the lead center for advanced life support. In order to support life in space for long periods of time, Controlled Ecological Life Support Systems (CELSS) which mimic natural biogeochemical processes are being studied. The benefits of bioregenerative systems are being maximized.

7. Marshall Space Flight Center (MSFC)

The website of MSFC does not hint at biomimetic activity at MSFC, however, a small article in Discover Magazine (GE3) indicates that there is a group of researchers involved in the development of evolutionary computing techniques for cooperative guidance of spacecraft. They are hoping to test the software in a spacecraft sometime in 2001.

8. Goddard Space Flight Center (GSFC)

GSFC is the lead center for the Nanosat Constellation Trailblazer mission whose mission is to validate methods for cooperative guidance of spacecraft systems. Among GSFC technologies onboard is a new type of microelectonic device that is more reliable and uses 20 times less power than proven technology, and an electrically tunable coating that can change its properties from absorbing the sun's heat when the spacecraft is cool to reflecting or emitting heat when needed.

GSFC is also funding academic research efforts in the development of bucky shuttles based on carbon nanotubes.

9. Stennis Space Center (SSC)

The Earth System Science Office studies coastal processes to support NASA's Mission to Planet Earth. They have a multidisciplinary staff that includes biophysics, biogeochemistry, oceanography, mathematics and engineering expertise, who conduct research from the subcellular to ecosystem scales. Development of remote sensing instrumentation is an area of research.

G. Other Government Labs

1. Oak Ridge National Lab (ORNL)

Around September, 1998, ORNL invited a group of scientists who were biomimetics experts to give seminars at ORNL. A committee headed by Bruce Jacobson was trying to determine what biomimetics activities ORNL should be investing in. When contacted by this Biomimetics Team about a year later, Mark Reeves, Director of the Bioprocessing Research and Development Center indicated that their decision was to educate their personnel on biomimetics so they can use this as a problem solving approach. They are willing to forge a partnership with NASA LaRC in biomimetics activities.

The emphasis of biomimetics activities at ORNL is biomedical applications. Their website indicates extensive work on biosensors. They recently developed the DNA biochip, a biosensor using DNA probes to diagnose genetic susceptibility and diseases. They've also developed a bio-MEMS sensor based on putting genetically engineered bacteria on a chip. The bacteria emit light upon interaction with certain chemicals. This sensor is projected to have environmental, medical, industrial and military applications. Their work also includes Computational Biosciences -- using computational approaches to problems such as drug design and catalysis.

2. Sandia National Lab

Sandia's mission is to "enhance the security, prosperity and well-being of the nation." In line with that mission, Sandia has developed a self-assembled ultra thin coating that is used as a sensor for dangerous air or water borne molecules. Jeff Brinker, the principal investigator for the sensor project, was awarded part of the $6.5M that NASA's Office of Life and Microgravity Science and Applications granted in August, 1999, for biologically inspired technologies. The new effort is for the "Biomimetic Self-Assembly of Hardened (Nacre-like) Nanocomposite Coatings for Transhab."

Sandia has multidisciplinary expertise that they are using to look at the physics and chemistry of nanotechnology. Sandia Labs is also doing research in smart structures. They have experts in vision science, multivariate analysis, pattern recognition and embedded computing design.

3. Los Alamos National Lab (LANL)

One of the core competencies at Los Alamos National Lab is Bioscience and Biotechnology, where they have multidisciplinary skills to study life processes, living organisms and human health. They are involved in biomedical research including optics and imaging, sensors, biomechanics, and robotics.

LANL won a 1999 R&D 100 Award for technology that provides a self-healing mechanism for personal protective equipment such as gloves, biohazard suits and boots, as well as containment vessels such as chemical drums.

4. Lawrence Livermore National Lab (LLNL)

Lawrence Livermore's mission is to apply science and technology to enhance global security, global ecology and bioscience. Biomimetic activities are reflected in some of the patents that LLNL holds. These include patents for a) a type of shape memory polymer whose phase transformation is triggered by changes in temperature and is used in medical applications b) sensors and actuators for medical applications c) the use of bacteria in biodegradation of organic contaminants and d) a neural network that uses a fuzzy membership function with adaptive parameters. They also have expertise in robotics and micromachining..

5. Forest Products Laboratory (FPL)

FPL is doing research which includes taking the structure and elements of trees and improving them for commercial applications. They are trying to develop new resins by learning from the naturally occurring resins in trees.

H. Research Centers

Biomimetics activities are pursued by various research centers around the world. The centers are typically characterized by the presence of multidisciplinary teams required for the success of biomimetics endeavors. Some key centers and the work they do are described below.

1. Centre for Biomimetics, University of Reading, U. K.
http://www.reading.ac.uk/AcaDepts/cb/home.htm

The leading biomimetics center in the world is the Centre for Biomimetics in the U. K. The center was established in 1975 and is now staffed by about fifteen scientists including biologists, engineers, chemists, biotechnologists and materials scientists working on several projects, with funding of over £400,000.

The Centre's strength is in the application of fracture mechanics to a wide range of complex materials. They have developed advanced test methods to interrogate plant materials, animal tissue and other composite materials and structures at all levels of the materials' structural hierarchy from the molecular level to the tissue and global structure. A sample of their projects includes mimicking bird bone composition with other components, applying the toughening mechanism of antler bone to general impact protection, design of a gel which acts like artificial muscle and designed based on worm locomotion, smart fabrics that mimic opening and closing of pine cones and insulation layers of penguins to make responsive clothing that transpires as a function of the wearer's activity state and using the toughening mechanism of wood to create materials with high velocity impact strength.

2. ASU Photosynthesis Center, Arizona State University, Tempe, AZ
http://photoscience.la.asu.edu/photosyn/default.html

The Photosynthesis Center at ASU is staffed by chemists, biochemists and plant biologists interested in understanding the process of photosynthesis. There are research groups exploring biomimetic photosynthetic systems in order to understand natural processes and how photosynthetic energy storage can be applied to other areas of science.

3. Centre for Self-Organising Molecular Systems (SOMS), University of Leeds, U.K.
http://chem.leeds.ac.uk/SOMS/soms.html

SOMS is housed at the University of Leeds and is focused on the study of biological-like molecular self-assembly to engineer materials with broad applications in electronics, sensors and medicine. Their research themes include tethered bilayers, self-assembled biomaterials based on peptides, discotic liquid crystals, self-assembly at surfaces and interfaces and self-assembling polymers and surfactants. Cross theme activities are self-assembling biocompatible surfaces and nanoscience and technology.

4. Weizmann Institute of Science, Rehovot, Israel http://www.weizmann.ac.il/home_all.html

Researchers at Weizmann Institute have backgrounds in Biology, Biochemistry, Chemistry, Mathematics and Computer Science and Physics. Some interdisciplinary projects at the institute include self-assembling liquid systems, self-assembled monolayers on electrodes, inorganic fullerene like nanotubes, mechanical properties of carbon nanotubes, biological composites from bones and structure/property studies of bones.

5. Sante Fe Institute, Santa Fe, New Mexico, **http://www.santafe.edu/**

The Santa Fe Institute (SFI) is a private, non-profit, multidisciplinary research and education center, founded in 1984. Since its founding, SFI has devoted itself to creating a new kind of scientific research community, pursuing emerging science. Operating as a small, visiting institution, SFI seeks to catalyze new collaborative, multidisciplinary projects that break down the barriers between the traditional disciplines, to spread its ideas and methodologies to other individuals and encourage the practical applications of its results.

Current Research Focus Areas are: adaptive agent simulation, adaptive computation, biological networks, cognition, computation, dynamics and inference, computational molecular biology and evolutionary dynamics, distributed learning, ecology, economics, evolution of human societies, evolution of language, evolutionary dynamics, evolving cellular automaton project, evolving local rules for global problems, HIV dynamics and evolution, origin of life, scaling phenomena, theoretical immunology and theoretical neurobiology.

SFI's Business Network is comprised of 49 companies and organizations which are committed to supporting the Institute. 1999 brought an increase in new members over the 1998 level, (seven new members with an additional six invoiced), even though there was some attrition (seven members) due to budgetary cutbacks, mergers, and acquisitions. The network continues to expand the scope of its membership, (exemplified by new internet companies AOL, Amazon.com and Cisco), its benefits, (improved and more timely information at the BusNet Web site), and its importance.

6. German National Research Center for Information Technology's Institute for System Design Technology (SET) http://www.gmd.de/

SET is a non-profit company funded primarily by DARPA. It has a Biomimetics Autonomous Robots (BAR) research team whose long-term goal is "to achieve robots that autonomously interact for an unrestricted time with a real world environment and that enhance their level of performance with experience gained from the ongoing interaction with the world." Research robots include snake robots and small crawling robots.

I. Industry

There are biomimetics activities going on in industry as well, although information from these projects is not always forthcoming. Information shown below are generally obtained from NASA's partnerships with industrial contractors and from news releases.

Several companies are involved in the development of smart structures. For example, Boeing is developing and testing smart structure systems for use in future advanced aircraft and other systems. They foresee benefits including improved aerodynamics and hydrodynamics flow control, vibration and noise suppression and optimization of lift and flight control surfaces. Boeing and Neurodyne are developing systems to detect damage using vibration sensors mounted on or embedded in the structures. Aerotech and the USAF are using smart structures to create a variable camber missile fin. Allied Signal Aerospace Co. is working with the ONR to apply smart structures ideas to space applications.

Some commercial companies have used biomimetics as an approach to solving engineering problems, the most notable being AeroVironment, Inc. (http://www.aerovironment.com) which designs and manufactures long endurance UAVs, and which also designed, built, and flew the most successful micro-air vehicle to date in the DARPA program. Aerochem Corp. was recently awarded an SBIR to study "Biomimetics Based Design for Damage Tolerant Airframe Panels." Professors Haftka and Rapoff from the University of Florida will be participants in this work.

Several Japanese companies including MITA and NEC are also studying and building snake-like robots. In the U. S., Xerox Palo Alto Research Center has work on snake robots.

Working with UCLA, Hewlett Packard is releasing a lot of results from their experiments in molecular switching and circuits. They are predicting several orders of magnitude reduction in size and power for circuits based on this technology with implications on organic data storage. Along these lines, IBM has invested in nanotechnology for many years and they continue to push nanoscale technology. Allied Signal has developed a carbon nanotube actuator.

For telecommunications applications, Lucent is looking into the neurophysics of goldfish vision.

VIII. Consultants

Several consultants considered experts in the biomimetic field were invited to come to LaRC to give overviews of their area of expertise; these areas coincide with the disciplines present at the Center. The objective of bringing the experts in was to provide an efficient mechanism for educating the team on the state-of-the-art in each of the disciplines. Since the biomimetic seminars were open to the whole center, the lectures served to introduce the researchers at the Center to the wide range of applications in which the biomimetic approach can be used. Information in this section include the name of the expert invited, his affiliation and area of expertise and the topics covered during the seminar as shown in the seminar abstracts. Documentation of attendance shown below suggests widespread interest in biomimetics among researchers at the Center.

A. Materials

1. ***Consultant:*** Ilhan Aksay, Princeton University, Area of Expertise is bioinspired processing of organic/inorganic composites, mostly based on the structure of abalone shell.

Bioinspired Processing of Organic/Inorganic Composites through Self-assembly

Friday, September 3, 1999, 10:00 a.m.

Bldg. 1205, Conference Room 222 (~100 attendees)

Bioinspired processing seeks to employ lessons from biology in the creation of synthetic analog composites with a unique spectrum of properties. Materials such as bone, teeth, and shells, are simultaneously hard, strong, and tough with unique hierarchical structural motifs originating at the nanometer scale. Our emphasis is on the development of enabling science to produce similar structures through self-assembly at the nanometer scale coupled with lamination and patterning methods at the microscopic scale with the ultimate goal being the development of high-performance composites. These nanostructured organic/inorganic materials hold promise for a multitude of applications, such as sensor/actuator arrays, optoelectronic devices, and medical materials. Three lessons from biology guide our objectives. The first and principal objective is to extend the scale of hierarchical design into the nanometer range to produce materials with improved properties. The structures of biological composites are hierarchically organized in discrete levels (nanoscopic, microscopic, and macroscopic) with distinct structural features at each level. In the case of biogenic hard materials, nature accomplishes this by growing hierarchically structured organic/inorganic composites in which soft materials organized on length scales of 1¡100 nm are used as frameworks for the growth of specifically oriented and shaped inorganics with small unit cells (~1 nm). The high modulus inorganic phase provides stiffness while the organic phase enhances toughness.

The second objective is to understand assembly and templating processes to enable us to design nanocomposites with desired interfaces and structures. Levels of structural organization are held together by specific interactions between components. For example, the structure of an abalone shell consists of layered plates of CaCO3 (~ 200 nm) held together by a much thinner (< 10 nm) "mortar" of organic template. Structurally organized organic surfaces induce growth of specifically oriented, dissimilar constituents catalytically or epitaxially.

The final objective is to understand the connection between hierarchical design and properties to facilitate optimization. Highly interacting levels are organized into a hierarchical composite system designed to meet a complex spectrum of functional requirements. As composite systems increase in complexity, they function at higher levels of performance.

2. ***Consultant:*** Stephen A. Wainwright, Duke University, Area of Expertise is functional morphology of plants and animals, structural basis of mechanical function in biomaterials and organisms, adhesion, lubrication, flexibility and role of fibers in organism design.

Biomimetics Seminar: Swimming by Design: Fish, Whales, and Submarines

Tuesday, November 2, 1999 10 am

Reid Conference Center (~130 attendees)

What can we learn from design in Nature? Manmade structures are often large, rectangular, rigid, and dry. Nature's living structures are small, curved, soft, and wet. Animals are Nature's answer to the problem of building mobile machines that are driven by a contractile polymer (muscle). The framework of these machines is mostly collagen, a high modulus protein fiber. Parallel fibers make a tendon for transmitting muscular force. Sheets of fibers and hollow cylinders made from them (such as guts arteries, and a shark's skin) have properties that depend on the orientation of fibers. A design feature in many animals is a fibrous skeleton that has mechanical advantage without levers. Copying Nature is costly and seldom effective - being inspired by Nature's designs can generate new materials and gadgets and may pay huge dividends.

B. Structures

Consultants: Andy Rapoff and Rafi Haftka, University of Florida, Area of expertise is optimization of engineering structures based on mimicking bones.

Biomimetic Structures and Materials Research at the University of Florida, Gainesville

Wednesday, September 29, 1999, 10:00 a.m.

Bldg. 1222, H.J.E. Reid Conference Center Auditorium (~90 attendees)

From the micro up to the macrostructural level, skeletal tissues and structures have evolved to be remarkably damage tolerant: the metabolic expenditure to form and repair the skeletal system is high, and the ability to affect repairs diminishes with age. The weight bearing long bones of the human skeleton contain numerous, naturally occurring holes (foramina) where blood vessels and nerves pass into the center and throughout the bone. Bone formation is such that loads are distributed about foramina with very low stress concentrations. This seems to be accomplished by an optimal, local directionality displayed by the compliant fibrillar protein (collagen) network surrounding the foramina and by judicious use of the stiffer, heavier mineral phase. Our current research focuses on identifying foramen shape and fiber directions and density gradients about foramina using microscopic and radiographic techniques. Mechanical testing can demonstrate the effect of the local microstructure on producing low stress concentrations. Our long term goal then is to implement similar strategies for designing man made structures with advanced fabric composites, with variable fiber fraction and multiple fiber systems. However, with hole shape, fiber orientation, fiber type, and volume fraction all being variables, the design problem may become computationally intractable. To allow detailed optimization of engineered structures with a multiplicity of design variables, designers could use solutions from nature to allow them to guess the nature of the optimal solution. Expert systems can be developed that will help designers to narrow options and to start with good initial guess of a structural design for a given set of requirements on hole areas and loading.

C. Controls

Consultant: Vasant Honavar, Iowa State University, Area of expertise is artificial intelligence.

Biomimetics Seminar: Neuromimetic Adaptive Autonomous Intelligent Systems

Tuesday, September 28, 1999, 10:00 a.m.

Bldg. 1222, H.J.E. Reid Conference Center Auditorium (~ 60 attendees)

Neuromimetic or biologically inspired approach offers a promising to designing adaptive intelligent, autonomous systems that need to function effectively in a priori unknown environments. In this talk, I will present one example of such a system which was designed and implemented in our laboratory. This system was designed to acquire and utilize, for localization, and navigation, spatial representations of a priori unknown environments. The design of the system was motivated by results of anatomical, physiological, and behavioral experiments in animals. In this talk, I will briefly review the relevant data and their relation to our computational model of spatial learning and localization. The proposed model includes a computational characterization of the hippocampal formation a brain region that has been implicated in spatial learning in animals). It can be understood in terms of Kalman filter based tools for information fusion from multiple uncertain sources. The resulting model not only explains neurobiological and behavioral data from rodent experiments, but also allows a robot to learn a place-based metric representation of space and to localize itself in a stochastically optimal fashion. I will describe an algorithmic implementation of the model and results of several experiments that demonstrate its capabilities. These include the ability to disambiguate perceptually similar places, scale well with increasing errors, and automatically acquire spatial information at multiple resolutions.

Time permitting, I will also briefly summarize our ongoing work on evolutionary approaches to synthesis of neuromimetic systems and our work on distributed knowledge networks - multi-agent systems for information retrieval, fusion, assimilation, organization, and data-driven knowledge discovery and problem solving using heterogeneous, distributed sensors, data, and knowledge sources.

D. Aerodynamics

Consultant: Michael Dickinson, Univeirisity of California, Berkeley Area of expertise is aerodynamics and neurological mechanisms of insect flight.

"The Aerodynamic Basis of Insect Flight"

Monday, September 13, 1999, 10:30 a.m.

Bldg. 1222, H.J.E. Reid Conference Center Auditorium (~120 attendees)

An engineer was once credited with proving that a bumblebee could not fly. The difficulty for this anonymous individual (and many other researchers throughout the past century) is that the application of steady-state aerodynamic theory to the wing motion of most insects predicts forces that are much too low to keep an animal aloft. The failure of steady-state theory has fueled the search for unsteady mechanisms that could account for the elevated performance of insect wings. One mechanism that has emerged from this search is delayed stall. Insects translate their wings at extremely high angles of attack that would result in stall under steady-state conditions. However, because the wings translate only a short distance during each stroke they never reach stall, but rather reap the benefits of a transiently stable leading edge vortex bubble. Such bubbles have been visualized on two- and three-dimensional models of flapping wings and clearly contribute to elevated flight performance.

Although delayed stall is undoubtedly important, it only begins to explain the elevated flight performance of insects. Unfortunately without being able to directly measure the time course of force production throughout the stroke, it has been difficult to identify additional unsteady mechanisms. In order to facilitate this search, we have constructed ROBOFLY, a large dynamically scaled model of a flapping fruit fly. Each 25 cm long wing is capable of three rotational degrees of freedom driven by computer-controlled stepper motors. The flapping model sits in a 1m x 1m x 2m tank of high viscosity mineral oil, which along with a flapping frequency of 170 mHz, establishes a Reynolds number of approximately 200.

In this lecture we use ROBOFLY to discuss the aerodynamic mechanism involved in the flight of insects.

E. Systems Engineering

Consultant: Greg P. Carman, University of California, Los Angeles, Area of expertise is smart materials.

“Active Materials Research at UCLA”

Wednesday, September 15, 1999, 10:00

Bldg. 1205, Conference Room 222 (~80 attendees)

Piezoelectric, magnetostrictive, and shape memory alloys are now a focal point for a variety of research and development activities due to the exceptional promise these materials offer when compared to passive material systems. There exists a number of studies indicating the potential advantage of using these materials in adaptive structures, however, fundamental issues such as inadequate force, displacement and bandwidths continue to prohibit their use. To overcome these problems my group manufactures several different actuators/devices, conducts experimental studies evaluating combined electro-magneto-thermo-mechanical response, and predicts their behavior in the context of designing mechanical systems. In this presentation I will provide an overview of three specific topics being studied in the Active Materials Lab at UCLA, namely thin film shape memory alloys, magnetostrictive composites, and piezoelectric compact hybrid actuators. The thin film shape memory alloy work focuses on overcoming the frequency limitation of “bulk” SMA materials. The magnetostrictive composite work focuses on developing novel damping approaches that rely on inherent non-linearities eliminating the need for power supplies or solenoids. The piezoelectric compact hybrid actuator focuses on increasing the displacements by using frequency rectification approaches.

F. Lessons learned from our consultants

1. Afternoon session with the consultants

Types of questions that the consultants were asked ranged from details that were extensions of their talks, which were necessarily specific to their area of expertise, and more general questions regarding working in the area of biomimetics. The general questions were typically along the lines of:

a. What are the funding sources for biomimetics?

b. What types of work are currently being funded?

c. What area of biology has been most useful in your biomimetic niche?

d. Where is the area headed?

e. What are some of the unresolved issues in your area?

f. What are the key areas required to do biomimetics in your field?

g. How can biomimetics be used to solve aerospace problems in an environment where no biological system can survive?

2. What did we learn?

Much of the information gathered with the questions asked above have been distributed as appropriate throughout this report. Below are some useful information/advice reiterated by more than one of the experts, that do not fit well in the other sections.

The Center has strengths in various engineering specialties and has the advantage that these various disciplines coexist in one location. In order for biomimetic activities to succeed, multidisciplinary groups must work together towards the same goal. The Center certainly has most of the disciplines required, but efforts have to be made to establish cross discipline interactions. The human resources present at the Center are further strengthened by the available facilities that are not accessible to most university researchers due to the prohibitive infrastructure costs involved. The resources available here should make it possible for LaRC to make contributions to biomimetic activities in other institutions via collaborative interactions with established groups who do not have facilities that would enhance their work. We should capitalize on our strengths and look to biomimetics as a tool that enhances our problem solving capabilities.

It was a consensus that while engineers are receptive to looking for biologically inspired solutions for engineering problems, there is great difficulty in identifying biologists who are willing and able to interact/communicate with engineers. This shortage in biologists who are inclined to work with engineers can have implications if the decision comes about to hire biologists who can help engineers at LaRC find solutions to aerospace issues encountered at the Center. It is advisable to hire biologists as consultants for specific problems, primarily to point Center engineers to the right biological system to investigate.

IX. Funding

Funding is a key component in research. It drives the growth or demise of research areas. In many ways, biomimetics activities are considered long term, high risk/high payoff research projects. It is not surprising therefore that work in this area is mostly sponsored by the government, rather than by industry, whose goals tend to be more short term.

A. Military Funding Sources

The Department of Defense invests in long term basic research where significant breakthroughs from high risk/high payoff research can result in key technologies that enhance the military's capability. A large portion of their research dollars go out to universities, other government labs, non-profit organizations and private industry. Each branch of the military has an office that oversees these programs.

1. Defense Advanced Research Projects Agency (DARPA)

The most recent and comprehensive DoD-sponsored biomimetic flight research effort is the DARPA Micro-Air Vehicle program. This work attempts to directly mimic biological flight systems for stealthy surveillance in a battlefield environment and contains both fixed wing and flapping flight vehicles. The web site summarizing the goals of this program can be found at http://www.darpa.mil/tto/Programs/mav.html.

2. Office of Naval Research (ONR)

Currently, the Office of Naval Research (ONR) is sponsoring a wide variety of research studies on the locomotion of marine creatures, drag reducing morphologies, maneuvering techniques, biosensors, marine noise, biomimetic signal processing, biomaterials and processes, biotechnology.

3. Air Force Office of Scientific Research (AFOSR)

The Air Force, through the Air Force Office of Scientific Research (AFOSR), is sponsoring work in flow control, nano-structured materials, MEMS sensors and actuators, and insect-inspired guidance, navigation, and control.

4. Army Research Office (ARO)

The Army Research Office (ARO) is funding work on smart materials and structures, polymer chemistry, nano-composites, self-assembly, and nano-scale probes.

B. Civilian Funding Sources

1. National Science Foundation (NSF)

The NSF budget for 1999 was about $3.7 billion to fund approximately 19,000 fundamental research projects. According to Rita Colwell, Director of NSF, Congress has set aside $100 million to fund research in DNA and molecular computing, and another $26 million for terabyte computing (GE4). NSF funding constitutes about 20% of Federal support for basic research in academic institutions. Some interdisciplinary grants awarded that can have impact on NASA's mission include work in the area of Learning and Intelligent systems, Biosystems at the Nanoscale, and Life in Extreme Environments. In recognition of the need for scientists trained in multidisciplinary environments, NSF is seeding multidisciplinary graduate programs.

2. NASA

In August, 1999, NASA's Office of Life and Microgravity Science and Applications announced the selection of 14 researchers who will receive grants totaling about $6.5 million over four years to perform research in biologically inspired technologies. These new research efforts are part of a $12 million dollar program.

Eleven of the awardees were from universities, two were from commercial companies and the lone government lab that received a grant was Sandia National Lab. Information on the awardees can be found at the following website: ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1999/99-089a.txt.

3. NASA Institute for Advanced Concepts (NIAC)

NIAC funds proposals on revolutionary, advanced concepts in aeronautics and space. These advanced concepts should be aimed at becoming aerospace missions for the time frame of 10 to 40 years in the future. Examples of funded work include the development of a mesocopter, legged robots, intelligent satellite teams, self-transforming planetary explorers, and deployable mesh systems. Although NASA Centers do not qualify for grants from NIAC, researchers are encouraged to do collaborative work with funded investigators.

4. National Institutes of Health (NIH)

The National Institute of Dental and Craniofacial Research (NIDCR) funds work in the area of Biomaterials, Biomimetics, and Tissue Engineering with emphasis on the "development of natural and synthetic materials to be used for the repair, regeneration, restoration, and reconstruction of oral tissues and organs; on the development and improvement of evaluation and measurement systems for the characterization of implanted material properties; on their interactions as well as on their performance under the severity of the biological environment; and finally on the development and/or improvement of new alloy combinations, especially those that are mercury free." They are interested in smart implants, developing biocompatible and bioactive materials, modeling of biological tissues, using biomimetic structures for implantation, improved composite materials and adhesive sealants for restorative dental work.

X. Recommendations

The results of the information gathering phase of this activity make a compelling case for LaRC to initiate biomimetic activities. Biomimetics is a tool that can be applied to a broad range of problems, and while examples in the aerospace arena do not dominate the field, it is not due to inapplicability of this approach. Rather, as indicated above, research areas grow and die based on funding.

Two major reasons should drive LaRC's initiation of a biomimetics effort. First, among the characteristics common to biological systems are robustness, adaptability, autonomy, intelligence, energy efficiency and the ability for self-repair, self-healing and self-evolution,. All these are characteristics that would be desirable in systems developed for various aerospace applications as well. Second, LaRC has a unique infrastructure in place that combines the presence of a multidisciplinary research environment with desirable facilities that are not easily accessible to other research institutions due to the prohibitive construction and maintenance costs. While there may be a gap in the Center's biological knowledge and skills base, this deficiency is easily corrected by hiring biology consultants. These two reasons answer the questions "Why biomimetics for LaRC?" and "Does LaRC have the resources to make significant biomimetics contributions?" What remains then is the question of implementation.

The team considered two options for implementation. The first option is the traditional focused program, whose goal would be to design and build a vehicle biomimetically. This option has the advantage of providing a common goal to pull together a multidisciplinary team. However, it requires a large amount of money to initiate. Furthermore, confining the biomimetic approach to this focused program would not exploit its full potential as a problem solving tool/approach.

The option recommended by the team is to weave biomimetics into existing programs. The advantages of this option are: a) goals are already in place, since the programs are in place b) research and support personnel are already established and c) since biomimetics is only one of the problem solving approaches being used in a specific program, rather than the focus of the project, a smaller initial funding is required. A disadvantage for the second option is the potential difficulty that may be encountered in asking researchers to use an approach that they are unfamiliar with, and therefore will understandably be uncomfortable with. However, judging by the attendance in the biomimetics seminars organized by this team, as well as the plethora of ideas for potential research topics (Section XII) generated by small groups of researchers, there is evidence for the existence of a significant core of researchers who are willing to consider, or at least are intrigued by, this problem solving approach.

Biomimetics activities embedded in existing programs can be funded by one of three ways:

a) Allot a small percentage (~5%) of each program's funding to the biomimetics effort in that program. Effectively, each program is taxed a small percentage by the biomimetics component.

b) Use base research dollars to fund proposals that are competed, with the stipulation that the proposals must be biomimetic and have applications that can fit into a specific program. The latter requirement provides a mechanism for ensuring that the proposed biomimetics activity has relevance to problems of interest to LaRC.

c) Jerry Creedon proposed using Director's Discretionary Funding (DDF) to support projects that are chosen from proposals competed though the DDF process.

Regardless of the funding option used, it is recommended that there be a focal point for biomimetics who oversees all the activities that are scattered over a broad range of programs. The job of this manager is to provide a means of evaluating the Center's contributions in this activity by monitoring progress made in the various disciplines.

With this plan in hand, several potential areas of research were compiled by the team after defining some LaRC mission requirements.

XI. Mission requirements for Langley Research Center – Steve Katzberg

Since ASCAC deals with outside customers in aeronautics and space, an informal survey was done to identify high payoff areas for biomimetic applications. The response was spotty, with some space mission applications identified. Nevertheless, with the bulk of the Agency's money going into space missions and in view of the uniqueness of NASA's role in developing space technology, the missions were discussed.

Deriving resources *in-situ* for planetary missions is an obvious need to reduce launch vehicle IMLEO requirements. The use of aero-braking for earth entry helps to reduce mass to orbit but the necessity of carrying propellant and consumables (for manned missions) can best be alleviated via *in-situ* production from available planetary materials. For a Mars mission, biological-like processes, perhaps bio-engineered organisms, could extract oxygen from planetary CO_2 to produce oxygen for propulsion and organic materials for consumption. In addition, the use of biomimetic materials and processes offer the possibility of effective and, to humans, acceptable closed loop environmental control-life support systems. The long interplanetary flight is hazardous enough for robotic systems, but with manned flight, the mission becomes uncertain at best. The ability of space vehicles to repair leaks, reconfigure avionics or life-support, while common characteristics, in biological systems, are virtually unknown in spacecraft technology.

Virtually all spacecraft are automatic: systems operate in a constrained world of operational (or non-operational) possibilities. Biological systems on the other hand are autonomous and operate with a wide range of operational possibilities. Deep space probes, with long round trip time delays in communication, will never be successful without considerable autonomy. Autonomy will come from systems that can reconfigure, are situation-adaptable and have some reasoning-like functions. Neural nets have demonstrated the closest to the desired capability and when properly linked to appropriately designed subsystems may enable the desired system autonomy.

In general, the application of biomimetics to space missions is strongly dependent on whether the mission is manned or not. The selection of which mission type will determine the subset of biomimetics approaches which will be needed. Nevertheless, it appears that biomimetics techniques offer important advantages to space missions, with both mid-term and long range benefits.

XII. Potential Areas of Research

After collecting information from the internal and external survey and the consultant visits, the team held brainstorming sessions with small groups of researchers across the Center to generate potential topics of research. Below are the ideas that resulted from the sessions. Accompanying the ideas are write-ups indicating how the work is biomimetics, a logical starting point for the work, what the potential applications may be and resources required to start up the activity. Some of the ideas are better developed than others; maturity of the write-ups are dependent on availability of in-house expertise on the subject. They are all included here as ideas that may be pursued after further investigation of the literature. Some of the activities are discipline specific while some are multidisciplinary. They are organized as such below.

A. Materials

1. Liquid Crystals as Reversible Adhesives

Many land and sea organisms have the capability to grab and release objects or climb steep walls using specialized limbs (claws or tentacles). An alternative way to get around is the use of reversible adhesives such as those used by marine mussels and sea urchins. Recently a group in France published their initial results on a liquid crystal (LC) based material that shows reversible tackiness as a function of temperature (shown below). The drawback of this material is that it is heat activated (activation temperature is 37 ^{o}C) [1]. Being able to control the tackiness by means of an electric field will expand the range of potential applications which can include planetary exploration.

Research is required to identify the specific areas within NASA that have a need for this type of adhesives. Target properties such as degree of tackiness, speed of release, adhesion activation mechanism (electric field on/off, temperature etc.) required and use environment must be determined. Existing chemistry can be used as a basis for starting this work. They will be modified to achieve the specified goals. Expertise required for the work are synthesis and characterization skills and facilities available in the Advanced Materials and Processing Branch (AMPB). At the application and evaluation stage, structures expertise may be required and SEC will be needed for device fabrication and evaluation.

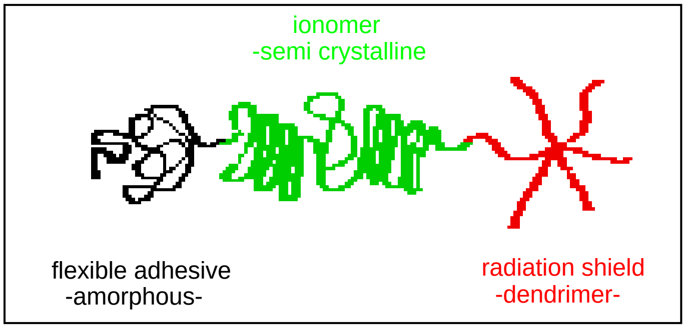
Literature

1. Crevoisier, G., Fabre, P., Corpart, J.-M., and Leiber, L., *Science*, 285, 1246 (1999).

2. Multifunctional Block Copolymers

All living organisms utilize highly complex and specialized macromolecules (*e.g.* DNA, proteins, peptides, and sugars) to perform various biological tasks. Although most of these macromolecules have complex chemical compositions on a primary and secondary level, it is often their tertiary structure, or supramolecular organization, that lead to materials with unusual chemical and mechanical properties (*i.e.* as found in spider silk, collagen, and elastin).

For a long time polymer chemists were limited with respect to polymer architectures. On a primary and secondary molecular level one could access linear, branched or grafted polymers that could either be amorphous, crystalline or semicrystalline. Most polymers were synthesized with one specific function in mind, *i.e.* they were used as adhesive, film, or fiber. A technique, known as 'living anionic polymerization' has provided the organic polymer chemist with a tool to go beyond those limitations. We can now chemically combine polymers with different chemical and physical properties in one polymer backbone. As in nature, polymers can now be synthesized in a fashion that allows us to obtain materials with molecular control at all three levels [1]. A potential application would be a self-healing coating such as the **ABC**-tri-*block*-copolymer depicted below. While the amorphous **A-block** is tailored to adhere to a specific substrate, the **B-block** provides self-healing and the dendritic **C-block** acts as a radiation shield. Self-healing systems are rare at the moment and the ones available are single component ionomer based systems. This means that the self-healing properties can be excellent but adhesion and radiation protection need to be added separately. However, the ionic character of the ionomer moiety will lead to incompatibility problems. Utilizing block copolymer technology will allow us to 'tailor-make' polymer based coatings that combine adhesion, self-healing and radiation protection in one polymer backbone.



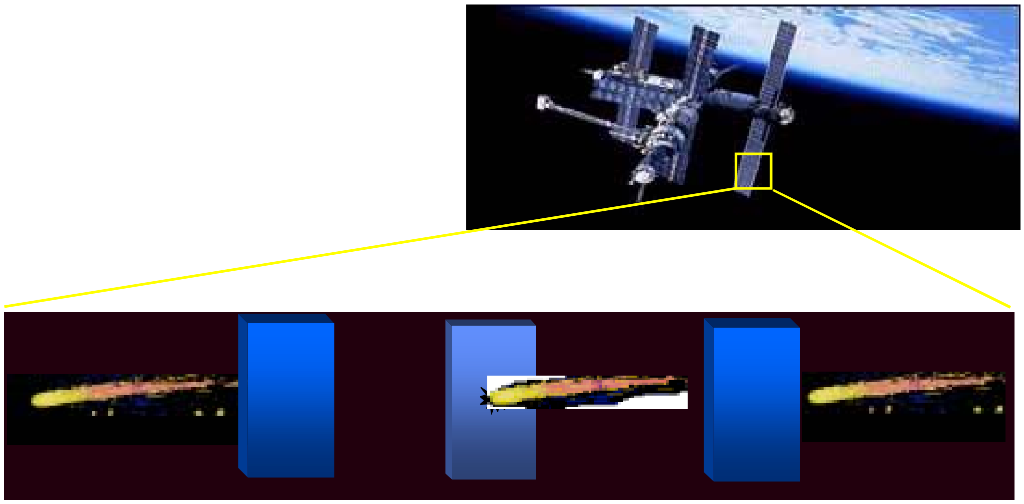
Researchers involved in this research will be the following: AMPB for material synthesis and characterization and Structures personnel for application and evaluation. Existing programs that would benefit from these novel multiphase materials would be: Reusable Launch Vehicles (RLVs), International Space Station (ISS), Morphing Aircraft/Adaptive Vehicles, Ultra-light Structures (solar sails) and Space Durable Polymers (coatings).

Literature

1. Ruokolainen, J., Saariaho, M., Ikkala, O., ten Brinke, G., Thomas, E. L., Torkkeli, M. and Serimaa, R., "Supramolecular Routes to Hierarchical Structures: Comb-Coil Diblock Copolymers Organized with Two Length Scales," *Macromolecules*, **32**, 1152-1158 (1999).

3. Development of Self-Healing Antifouling Material

Biological systems are characterized by their ability to repair wounds and heal so that the system can continue to functional like new. Synthetic materials are generally incapable of this function. The work proposed here is to develop a new ionomeric material whose ionic character will allow it to heal when punctured. The shear force produced by the puncturing should allow the material to flow momentarily and heal due to ionic interactions that are activated by the shear energy. Antifouling is an added dimension that will result in a self-cleaning material. This is important in the reduction of drag on flying or swimming vehicles. Antifouling will be achieved by incorporating fluorinated groups in the material to lower its surface energy and discourage contamination from sticking to it. This is a materials development effort which will require the expertise of synthetic and physical polymer chemists to develop methods for synthesis and characterization of the materials. Skills and facilities are available to start this work. The development of this new material will result in cost savings because self-healing will eliminate or delay the replacement of parts of space structures for instance. Self-healing materials would be valuable in most programs like RLV and Ultra-light structures whether for space or aeronautic applications.



4. Self-Healing Composites

Synthetic structures do not possess the self-repairing capacity of natural systems such as bones and other tissues. This is disadvantageous in any application because while minor damages may be simply inconvenient, this can lead to major damages that result in catastrophic failure. Self-healing composites used in structures offer the possibility of obtaining high strength, lightweight structures that are robust due to their self-healing characteristics. In order to achieve this, potential healing mechanisms will be investigated. New ionomers with target temperature, modulus and strength properties can be synthesized for composite matrices. Alternatively, encapsulated matrix precursors may be embedded in the matrix resin to provide a means of sealing cracks when they occur. Prototype composites can be developed with these new matrix resins. Optimum conditions for the processing of these self-healing systems must be investigated. The resulting lightweight, highly damage tolerant composites may be used in the Smart Materials program. Composite engineers and polymer chemists will be required for this work.

Literature

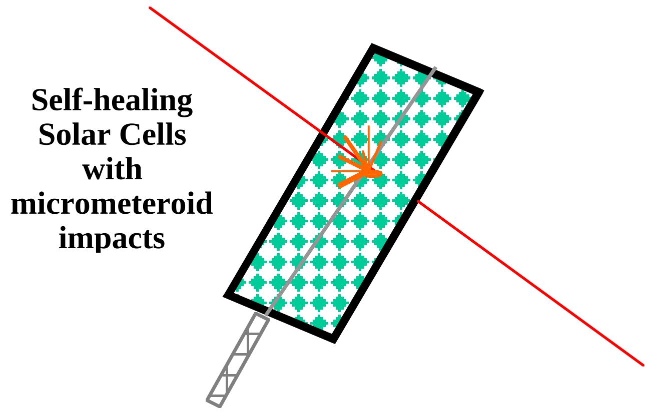
1. http://www.tam.uiuc.edu/Faculty/Sottos/Self-Healing_Composites/index.html

5. Interfacial Disbond Repair

Failure in composites can occur at the fiber/matrix interphase resulting in delamination, which leads to catastrophic failure. This may be alleviated by using fibers that have been functionalized on the surface such that they respond to radiation. If the matrix resin is reactive in this manner as well, this will provide a mechanism for disbond repair in space where radiation is present. Instead of making materials completely inert to radiation in the environment, a multiphase material can be designed so that while the outer layer is radiation resistant, tears or delamination will expose surfaces that react with the environment to provide a self-repairing mechanism. This will mimic the self-repairing characteristics of skin tissues. This effort can be initiated in AMPB which has expertise in materials development and environmental effects. Interactions with structures experts in SMC will accelerate development of structures that can be made with these materials.

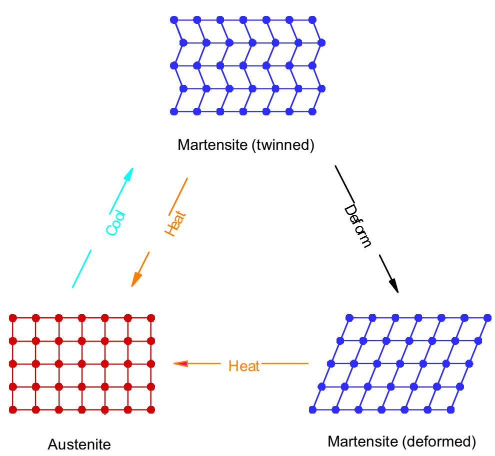
6. Self-Healing Solar Cells

Systems in the space environment suffer damages from a variety of sources. An example of considerable importance is micrometeroid damage. For a solar cell, the accumulated degradation of performance from micrometeoroids can be severe and can be catastrophic. Materials which are compatible with silicon or gallium arsenide that are capable of isolating damaged areas would permit much lower mass or much longer in-space life for solar cells, by far the most used power source. Mechanisms by which biological systems such as abalone shells limit damage propagation will have to be investigated. Interaction between AMPB personnel with ASCAC personnel who have information on mission requirements for space systems need to be initiated for the development of self-healing solar cell materials.



7. Shape Memory Alloys

Shape memory alloys are a class of smart materials that undergo a solid-solid phase transformation in response to changes in temperature and/or applied stress. The interaction of temperature and applied stress in driving the phase transformation can be used to exploit phenomena such as the shape memory effect and pseudo-elasticity. Both phenomena are manifestations of a diffusionless, thermoelastic, martensitic transformation. Extensive work has been done to characterize shape memory alloy materials, both qualitatively through theoretical models [1,2] and quantitatively for particular alloy compositions [3-5]. However, much is yet to be learned about their metallography, thermoelastic characteristics, and potential for biomimetic applications.



Cooling the material through the transformation temperature range from the high temperature austenitic state drives the martensitic transformation. The shape memory effect (SME) can be described in simple terms in the following manner. A SMA specimen can be easily deformed in the low temperature martensitic condition and can be returned to its original configuration by heating through the reverse transformation temperature range. This type of SME is termed free recovery. Conversely, in a constrained recovery configuration the SMA specimen is prevented from recovering the initial strain and a large tensile stress (recovery stress) is induced. A situation in which the specimen performs work (deforms under load) is called restrained recovery. The most common pseudo-elastic behavior exhibited by shape memory alloys is the production of martensite by applying stress to an austenitic specimen. While the SME and pseudo-elastic phenomena might be considered inherently biomimetic (i.e. autonomous reaction to environmental stimuli), the biomimetic nature of shape memory alloys is much more obvious when considering many of their applications.

Most biomimetic applications of SMAs identified to date fit in the constrained or restrained recovery categories. In most of these applications, the SMA actuator(s) behave in a manner analogous to muscle tissue in a biological system. For example, SMAs have been embedded in composite structures in a constrained recovery configuration such that the recovery stresses induced due to an elevated thermal environment (e.g. high speed aerospace vehicles or structures in the vicinity of jet exhaust) cause an adaptive structural stiffening effect. This technology has tremendous potential for improving the dynamic response, sonic fatigue, and noise transmission characteristics of flexible structures in harsh environments and is very weight-efficient relative to conventional approaches. A similar restrained recovery application entails embedding actuators in a structure in agonist-antagonist pairs at off-axis locations to allow shape control of the structure (e.g. jet engine inlet, aerodynamic control surfaces). This approach has enormous implications for drag reduction by reducing flow separation (hingeless control surfaces) and also has significant weight benefits. This latter application can also be accomplished, without embedding the actuators, by placing the actuators within a cavity formed by the structure and allowing them to work against the 'bias-spring' stiffness of the structure. Finally, other restrained-recovery, biomimetic applications exist such as thermally activated release devices and actuators for robotic movement.

This work is highly multi-disciplinary and requires the efforts of personnel with experience in metallography, metallurgy, mechanical testing, composite fabrication, actuator integration, thermoelasticity, and structural dynamics/structural acoustics. Work currently being performed spans the Metals and Thermal Structures Branch (S&MC), the Advanced Materials and Processing Branch (S&MC), the Structural Acoustics Branch (AAAC), and the Test and Development Branch (SEC). Extension of this work to control surface shape control would require involvement of the Aeroelasticity Branch (S&MC), the Configuration Aerodynamics Branch (AAAC), and other personnel in the SEC.

Literature

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2. Brinson, L. C., "One Dimensional Constitutive Behavior of Shape Memory Alloys: Thermomechanical Derivation with Non-Constant Material Functions," *Journal of Intelligent Material Systems and Structures*, **4**(2), 229-242 (1993).

3. Liang, C. and Rogers, C. A., "One-Dimensional Thermomechanical Constitutive Relations for Shape Memory Materials," *Journal of Intelligent Material Systems and Structures*, **1**, 207-235 (1990).

4. Cross, W. B., Kariotis, A. H., and Stimler, F. J., "*Nitinol Characterization Study*," NASA CR-1433 (1969).

5. Jackson, C. M., Wagner, H. J., and Wasilewski, R. J., "*55--Nitinol The Alloy with a Memory: Its Physical Metallurgy, Properties, and Applications*," NASA SP-5110 (1972).

8. Non-Metallic Shape Memory Materials

Shape memory materials undergo phase transitions as a function of external stimuli like temperature and pressure changes. This simulates plant and animal behavior in response to stimuli-tropisms. Most existing shape memory materials are metal alloys. However, a recent publication on “Smart” Rotaxanes suggests that the shape memory characteristic can be manifested by non-metallic materials as well [1]. In the case of the published work, this was accomplished with rotaxanes, which are macrocyles that are mechanically linked together. Other types of chemistry and architectures may be explored to create non-metallic materials with shape memory. One way to approach this is to synthesize block copolymers which phase separate into two domains. The two phases will have different softening temperatures, so that two different states can be attained as a function of differences in exposure temperature. Alternatively, the two phases may differ in electrical properties so that they respond to electrical stimuli differently enough to create two separate states. This work will require the involvement of polymer chemists at AMPB and device fabrication experts at SEC. This material can be used to make lightweight, temperature controllable systems that are cheap and easy to fabricate. It will fit well into the Smart Polymers activity.

Literature

1. Clegg, W., Gimenez-Saiz, C., Leigh, D. A., Murphy, A., Slawin, A. M. Z. and Teat, S. J., “Smart Rotaxanes: Shape Memory and Control in Tertiary Amide Peptido[2]rotaxanes,” *J. Am. Chem. Soc.*, **121**, 4124-4129 (1999).

9. Field Effects for Self-Assembly

Cellular systems are self-assembling systems that adapt to changes in their environment. Ionomeric systems can be developed that react to electric fields. In fact, electrorheological fluids are known to stiffen and soften based on the presence or absence of electric fields. This characteristic can be exploited to reconfigure systems. Involvement will be required of physical and synthetic polymer chemists. Some skills and facilities are already available from the Smart Materials personnel on hand. Ability to align materials with fields can result in the potential for multifunctionality using the same chemistry. Reconfiguration of a material will be possible so that one material can perform more than one function as needed. This will cut down on the amount of cargo that may need to be carried onboard the Space Station for example, and will make for improved efficiency and lower costs.

10. Magnetic Self-Assembly

Multifunctionality is a characteristic common in biological systems. For instance, our arms can be adapted into different configurations as required by tasks at hand. In contrast, synthetic structures are usually static and made for a singular function. The possibility of imparting magnetic properties to structures should be investigated. Magnetic particles may be placed at strategic locations in a composite or metallic structure to create reactive or self-assembling structures that respond to magnetic stimuli. Potential applications include deployable, self-assembling space structures. Such an effort can be initiated between MTSB and AMPB.

11. Rigidizing Soft Polymers

Flexible polymers are very easy to transport into space because of the ease of packing. However, most applications in space require a rigid space structure. One could envision soft polymer ropes or films for easy transportation, which would utilize the space environment to react and become rigid. These polymers would need to be reactive in the presence of radiation or atomic oxygen after being deployed into the desired shape. Research would involve new polymeric materials designed to react in the space environment. To date, we have been more concerned with space stable (unreactive) polymers.

Work in this area should begin with a survey of the literature to determine who is working in the area and how much work is currently ongoing. It is assumed there is a limited amount of work being done at the DOD, DOE or Universities.

Current SOA utilizes utilizes materials in their final chemical state and relies on mechanical methods for higher packing efficiency. For example, folded or inflatable structures are transported to space and unfolded or inflated in space. This concept would be a first step in developing space structures from raw materials in space, except that only partially formed materials/structures would undergo the final change in chemistry in the space environment by becoming fully rigid. Polymer/material scientists will be needed to design and synthesize the new materials containing groups which react in the presence of the atomic oxygen or radiation present in the space environment. Research should reside in the Structures and Materials Competency and be led from the Advanced Materials and Processing Branch, although polymer/materials scientists present at NASA LaRC would have to refocus their research toward new materials systems.

12. Liquid Crystal Elastomers as Artificial Muscles

The idea is to mimic muscle tissue as found in living organisms, including related tissues such as collagen and elastin. This synthetic muscle, or actuator, can be activated using external stimuli, *e.g*. light, pressure, chemical energy, temperature, electric potential *etc.* We propose to expand on novel liquid crystalline elastomers (LCEs) that have recently been developed by Finkelmann *et.al*. [1]. LCEs are more promising than the peptide [2] and ionic gel [3] based muscles that are under intensive investigation at the moment. The latter require aqueous environments in order to operate, significantly limiting their range of application. LCEs, however, are conventional films built around a flexible polymer backbone with pendant electro-active liquid crystal (LC) side-groups that are oriented and cross linked when the film is stretched. The LC units in this elastomeric network can interact with an applied electric field resulting in film contraction. When the field is turned off, the film relaxes back to its original shape. LCEs have been demonstrated to work in both contraction and bending mode.

To date, state of the art synthetic muscle materials are based on either peptides (Urry *et.al*) [2] or ionic gels (Shahinpoor *et.al*.) [3]. Both have the major disadvantage that a humid environment is required, which means that they need to be encapsulated in order to function in a dry environment. Using liquid crystalline elastomers will circumvent this problem and it will allow us to tailor-make a material suitable for any environment.

Initial efforts will identify the specific areas within NASA that have a need for this type of actuator, determine the desired properties for a synthetic muscle and the environment in which the material needs to function. The Finkelmann group has synthesized a few materials that could operate in a limited temperature range. We need to modify the chemistry to match our needs . Fabrication of film based prototype actuators may be accomplished in about two years.

Research will involve synthesis and characterization skills at AMPB and device fabrication expertise in SEC. The material can fit into the Morphing Aircraft/Adaptive Vehicle program as sensors and in the manufacture of ultralight structures. Potential applications include robotic manipulation for planetary exploration.

Literature

1. Finkelmann, H., Kundle, I., Nishikawa, E., *Macromolecular Symposia*, **117**, 11 (1997).

2. Urry, D.W., *Angew. Chem. En. Ed*, **32**, 819 (1993).

3. Shahinpoor, M., Bar-Cohen, Y., Xue, T., Harrison, J.S., Smith, J., “Ionic Polymer-Metal Composites as Biomimetic Sensors and Actuators-Artificial Muscles,” In Field Responsive Polymers, Khan, I.M., Harrison, J.S., (Eds.), American Chemical Society: Oxford University Press, 1999, Chapter 3.

13. Low Moduli Polymers for Noise Reduction

Owls are capable of silent flight due to the downy feathers on their wings. This mechanism may be adapted to reduce noise generated especially by smaller GA airplanes. Soft/low moduli polymers can be syntheszed and used as wing coatings to absorb noise. Any additional weight due to the coating should be very little, and cost will be no more than SOA coatings. Operability will need to be tested. Interactions of materials development personel with aerodynamics and fab personnel will be necessary in the development and testing of this coating. Lower A/C noise with light-weight material can be applied to any aircraft Noise Program.

14. Organic Mortar

Hierarchical structures are rampant in natural systems and was found to provide a toughening mechanism for inorganic components such as calcium carbonate, which in the monolithic form does not have very impressive mechanical properties. Knowledge regarding this can be translated to the composite structures that are widely studied for aerospace applications. Novel binders with inorganic fillers at the nano-level can be developed to mimic natural inorganic/organic hybrids such as abalone shells. The work should result in a nano-scale composite structure which can have high temperature capability and damage tolerance. This activity will require the expertise of polymer chemists and composites engineers all present in S&MC.

15. Advanced Reinforcements

Advanced reinforcements similar to those found in insect wings can be developed for novel composites. This may be achieved by using functionalized carbon nanotubes and other advanced fiber forms. Successful development of these reinforcements will result in new lightweight, efficient structures from the stiffness viewpoint. Cost may be an issue initially, but there could be trade-offs once use volume increases.

LaRC expertise in materials and composite development can be combined with nanotube expertise at Rice University and JSC for this effort. Carbon nanotubes can be functionalized at Rice/JSC and LaRC will perform the development work to use these nanotubes as a mechanism for composite reinforcement. This activity can contribute to the Smart Materials and Ultralightweight Structures programs.

16. Organic/Inorganic Hybrids

Zeolites are a class of crystalline alumino-silicates with a three dimensional structure that is formed by connecting silicon and aluminum atoms through oxygen's atoms. A large variety of natural and synthetic zeolite structures are known. A zeolite can be visualized as an ordered network of channels and cavities (*micropores*) and are therefore very "empty" structures (e.g. the density of most zeolites is < 1 g/cm^3 with an internal surface area of 900 m^2) which makes these materials virtually *all* surface [1].

Although less known, zeolites also have very interesting thermal properties. Most zeolites in their active form are stable up to 800 ^oC (1472°F). Increasing the temperature from this point, results in a chemical modification of the cages and an amorphous silicon-aluminum oxide (Al/SiO_2) structure is obtained which would be useful in thermal protection structures such as the tiles used on the space-shuttle. To date, however, no reports have been made with respect to the use of zeolites in thermal structures.

Fabrication of precursor polymer-zeolite micro-composites which can be used in a variety of tunable thermal structures should be possible. The unique chemical functionalities in the zeolite cages can be used as chemical 'docking-sites' for polymers. The strong physical-chemical interaction between a polyamic acid -- the precursor to polyimides -- and the functionalities in the cages, will lead to a very efficient particle coating which is essential for a high quality micro-composite with a high particle loading. The resulting polymer-zeolite precursor can then be processed into any desired shape followed by sintering.

Potential applications for this material include:

- **Thermal structures such as disposable and/or permanent heat shields**: zeolite based structures reinforced with carbon-carbon might be considered as useful thermal protection materials for the Hyper-X program. One of the major engineering challenges of the X-43 is cooling the cowl leading edges. One of the approaches is to use water as a coolant. Zeolite based microcomposites can be useful here since water can be pumped through 'molecular channels' and effectively cool an under lying structure with a minimum amount of water. This will dramatically reduce the amount of water needed for cooling which will in turn reduce the weight of the vehicle considerably.

- ***In situ* fuel generation for propulsion systems**: zeolite based structures can be constructed such that they serve both as transport medium and fuel storage. The catalytic functionality can be used to break down hydrocarbon fuels in smaller fractions that feed directly into the combustion chamber.

- **Laser absorbent material and radiation shields**: thermal control on satellites (radiator panels)

- **Waste-removing abilities**: zeolites have been use to remove radio-active heavy metals from nuclear waste.

Other spin-offs include potentially interesting and useful electronic and optical materials, robust parting systems for advanced electronics, unique hybrids for precision tooling and wear resistant materials for rotating equipment. Because of the high porosity and bio-compatibility of zeolites, novel applications may even include biomimetic scaffolds for artificial bone, tunable bone sutures and collagen structures.

LaRC has the materials development and systems engineering skills and facilities to initiate this work and bring it to the device fabrication stage.

Literature

1. P. Ball, "Tunnel Vision," in *Made to Measure, New Materials for the 21st Century*, Princeton, NJ: Princeton University Press, 1997.

17. Bioadhesives

Barnacles and mussels produce adhesives that are water resistant. If this characteristic can be mimicked synthetically, it will be useful in applications such as tank sealants where adhesives have to be resistant to liquids. To date, much of the work in bioadhesives derived from marine creatures are done by Waite at University of California in San Diego [1,2]. Information from his work regarding mechanisms and chemistry of adhesion may be useful starting points in the development of biomimetic adhesives. While polymer synthesis and characterization capability exist in AMPB, the expertise of a biologist such as Waite may be required in a consultant capacity to aid in the development of this new adhesive. Development of this type of adhesive is not useful only in aerospace applications such as sealants, but will be extremely useful and interesting to the Navy and the shipping industry as well.

Literature

1. Hansen, D. C., Corcoran, S. G. and Waite, J. H., "Enzymatic Tempering of a Mussel Adhesive Protein Film," *Langmuir*, **14**, 1139-1147 (1998).

2. Deacon, M. P., Davis, S. S., Waite, J. H. and Harding, S. E., "Structure and Mucoadhesion of Mussel Glue Protein in Dilute Soluton," *Biochemistry*, **37**, 14108-14112 (1998).

18. Hierarchical Structural Materials

Biological organisms are organized hierarchically: cell – tissue – organ – system and also, at a more refined level, the function of tissues reflects their molecular structure, so that the sequence of amino acids in a protein defines its secondary and tertiary structure (fibrous versus globular, for example). The objective of this proposed activity is to assemble material systems through understanding molecular determinants of structure. The starting point for this proposed activity is a basic understanding of the shapes and interactions of macromolecules and the driving forces for such processes as crystallization and vitrification. Most of the work would involve SMC interacting with SEC who would help define multiple requirements such as rigidity and thermal management. Weight savings and processability are improvements that can result from this work. This activity would fit into the Computational Materials program.

19. Biosynthesis of Materials

The proposed work is to design structural/functional materials using biological building blocks such as sugars and amino acids. Genetic engineering of organisms may be required to produce the new materials. The starting point is a survey of the kinds of materials existing in nature. Natural materials would be adapted (simplified or functionalized) to facilitate construction of useful devices. To the extent that vehicle designers could incorporate material variations in their studies, this would be an ideal way to produce absolutely consistent molecules for evaluation as membranes or struts. Knowledge of modern molecular biology would be necessary, but many of the procedures are now automated. A consultant and some equipment would be needed. The work ties to existing activities in polymer synthesis and design. It should result in advantages in safety, recyclability, flexibility for long space voyages or planetary colonization.

B. Structures

1. Efficient Fuselage Structures

The fuselage can make up 40% of an aircraft's weight. Reducing this weight reduces the fuel consumption for a given mission and therefore reduces the CO_2 emissions. There are several ways to reduce the weight of the fuselage: 1) fabricate from lighter material such as a composite 2) go to a noncircular streamlined shape or make other aerodynamic improvements 3) optimize design for structural efficiency 4) improve joint between wings and fuselage to reduce weight and improve efficiency. CO_2 emissions could be reduced by 4.7% by reducing the weight of the fuselage by 35%. Operating costs would also be reduced by reducing the weight of the aircraft and the amount of fuel needed.

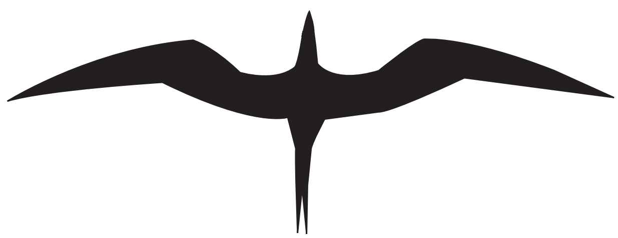
Bird bodies are not made from isotropic materials, but are constructed of a combination of layered soft and hard materials. Even advanced composites currently used are simple compared to actual bone, muscle, tendon and skin. Trees have fibers in numerous directions and adapt to wind conditions in ways man-made structures do not. Joints between wing and fuselage structures are heavily loaded and could be more efficient by eliminating many of the bolted connections and going to a more simplified and streamlined design. The joint between a bird's wing and body is far less complicated than that of an aircraft, yet it carries much load.

We can build off work done under the AST/ACT, HSR and BWB programs as well as numerous other programs the Center has been working in the last few years. The Boeing-Seattle ACT program developed manufacturing techniques well-suited to fabricating fibrous fuselage structures.

2. Ultralightweight wings

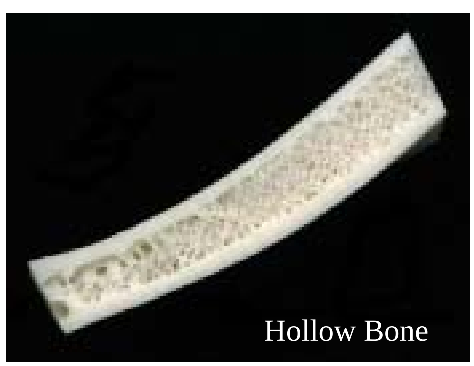
General aviation aircraft and unmanned aircraft could benefit from lightweight wing structures. The lighter the aircraft the less fuel needed, whether that fuel is conventional fossil fuel, solar energy or some other form. Reducing the weight of the structure would reduce the cost associated with operating a general aviation aircraft and could allow an unmanned aircraft to remain aloft longer.

Lightly loaded and small aircraft wings could be built to mimic the wing structure of large birds like the frigate bird which has a wingspan of 7 feet but whose skeleton only weighs 4 oz. This combination of dimensions is achieved by the use of hollow bones which could be recreated by using hollow composite tubes. Fiber orientations in the tubes could be tailored to flight loads and the need for conventional spars, ribs and numerous fasteners eliminated by using optimally designed structures. The technique could be applied to any lightly loaded aircraft. Its best application would be unmanned vehicles such as high altitude vehicles.



Frigate bird has a 7-foot wingspan
but its skeleton only weighs 4 oz.

This would be a combined structures and materials effort. Loadings would have to be determined and optimized designs be developed. Several manufacturing techniques would be considered to determine how to build the best tubes to meet all requirements in a cost-effective manner. A method for joining the tubes to each other and to the skin of the wing would also be needed.



3. High Impact Strength, Lightweight Structures

Tough structures abound in nature. Some examples include antler bone, mollusk shell and wood. An understanding of the toughening mechanisms in these structures may be translated into the design of materials and structures for aerospace applications. While there is a large body of literature on this topic, the key is to take the information and use it for aerospace applications. Much of the work done is academic and needs to be adapted to the design targets required in aerospace structures for vehicles. It is expected that biomimetics will enhance aerospace vehicles' reliability and safety.

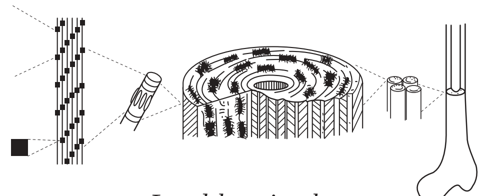
4. Building Porous Structures

Conventional aircraft are fabricated with spars, ribs and skins connected using fasteners. A more efficient design could be achieved with elimination of the ribs by inserting a porous filler such as a foam into the wingbox which is light, but could sustain enough load to maintain the wing shape. A metal, plastic or composite foam or other filler could be used as long as it met the stiffness, temperature and manufacturing requirements. This approach could tremendously simplify the wing assembly, improve efficiency and reduce operating costs by reducing weight. In addition, different regions of the wingbox could be constructed in different ways and porous regions could be used in areas where fuel and hydraulic lines or wires have to be run. The porous foam could be positioned to hold these lines in place so clips to stiffeners would not be needed. These wires and other lines are analogous to methods by which nutrients are transported through porous regions in bones and other natural structures where little load-carrying ability is needed.

Lightweight foam core

This would be a combined structures, materials and system engineering effort. Development of a technique to inject a foam into the structure would be required. Manufacturing development work would be done by materials people with input from structures people and the systems engineering organization.

Analysis of the material and prediction of its behavior under load would be needed. Testing of the technique with small and medium size subcomponents would be required.



Load-bearing bone

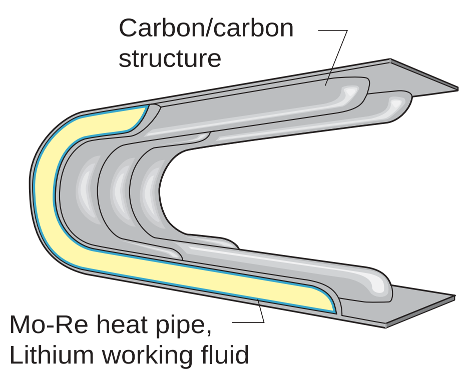
The technique could be applied to any wing structure, with extent of use being dependent on the type of foam material used and its interaction with fuel. The latter would limit usage to parts of the wing that do not carry fuel.

5. Multifunctional Hybrid Structures

In nature, structures perform a variety of different functions in addition to carrying load. Structural supports in nature are also a complex system of many different types of materials working together. Design of multifunctional structures out of a hybrid of materials (metallic, organic, and ceramic materials) mimics the multi-functional, multi-material nature of many biotic structures.

The objective here is to develop techniques to fabricate hybrid structures which perform multiple functions, such as primary structures which also perform heat management or power/energy generation and storage functions, or bone-like structures with hard protective and structural exterior having open celled foam passages used for fuel storage or communications routing in the interior.

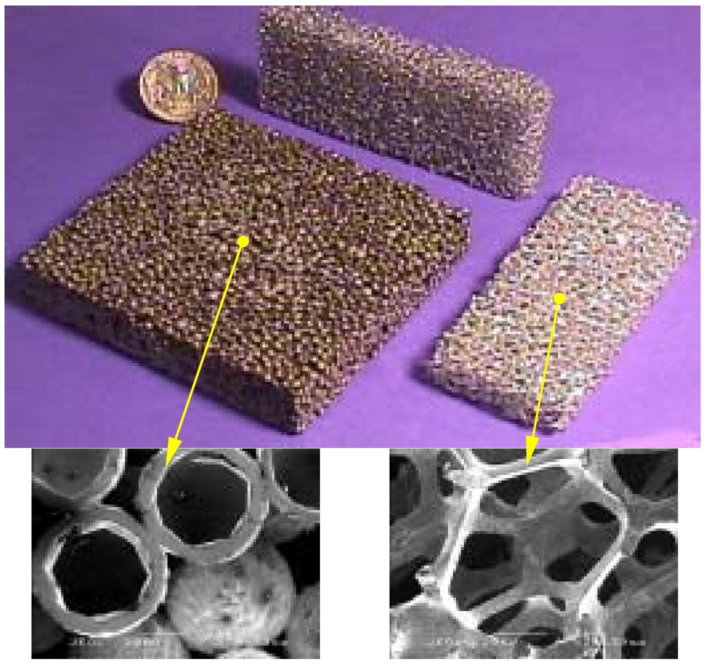
Multifunctional hybrid structures can eliminate redundancy, improve efficiency, reduce size, and simplify the overall systems by eliminating excess hardware. All of these functions result in significant weight savings which lead to decreased power requirements and cost. Simplification of the structures also reduces time and costs associated with assembly and maintenance. Implementation of multiple functions into the structure also provides the opportunity for miniaturization by eliminating the need for redundant systems. For example, if fuel is stored within the structure, fuel tanks and supports can be eliminated. Thermal management can eliminate supplemental insulation requirements, and energy development and storage eliminate the need for energy storage devices like batteries. A metallic structure which can also perform other functions can result in significant weight savings even over significantly lower-density polymeric materials due to the multitasking of the structural elements.



The steps for research start with a multidisciplinary approach to identify several functions which can be efficiently combined into a single structure. Materials selection, processing, and joining development must then be performed to determine materials and processes to satisfy applications identified. Structural design and analysis are required to optimize structure for load capacity while incorporating other functions. Secondary functions such as heat management, power generation, energy conversion and storage must then be analyzed and optimized. Finally, coupons must be fabricated and subcomponent panels with multiple functions tested to determine the structure’s ability to carry loads and perform other functions simultaneously.

6. Porous Metallic Structures

Structural members such as bones have a dense outer structure (compact bone) and a porous internal structure (spongy bone). Metallic structures can be fabricated with dense metal on the exterior load bearing regions, and porous metal (metallic foam) in the interior regions to mimic the structure of bones. The objective of this activity is to develop integrated structures that utilize emerging, closed-cell metal foams that perform the high temperature thermal protection, cryogenic insulation, and secondary structural (such as a sandwich core) functions in an integrated manner.



Syntactic Closed Cell Foam   Reticulated Open Cell Foam

The approach for this work involves examining internal bone structures to better understand the porosity, transition from compact to spongy bone, and region surrounding nutrient foramen which do not exhibit stress concentrations. A conceptual design study will then identify integrated airframe concepts that use metallic foams. Properties required for metallic foams to enable or to improve the integrated concepts will be identified. Metallic foams will be developed and evaluated to meet the requirements identified in the study. The most promising fabrication technique(s) will be identified and improved to produce candidate foams. The foams will be evaluated for thermal and thermal-structural properties. Joining practice will be investigated. Integrated concepts that show the greatest promise will be used as a basis to develop panels and subcomponents to validate thermal and thermal-structural performance.

This project will involve personnel from MTSB for material processing development and characterization, thermal analysis and structural design, MDB for durability analysis, structural design and analysis and ATTB for technical support. External collaboration with Georgia Tech and Sandia National Labs for metallic foam fabrication and development, and possibly some collaboration with NASA-MSFC for applications in launch vehicles will be needed.

Foams, which are formed by incorporating cellular pores in a solid matrix, are inherently lighter in weight than the bulk solid material. In many applications, weight savings may result in a more economical product or process. A cellular material has a lower bulk modulus than a bulk solid, which serves to increase the compressibility of the solid, decreasing the likelihood of stress related fracture due to thermal cycling or other stresses. Mechanical, electrical, and thermal properties of a structural foam can be controlled by varying the foam cell size and morphology, and also by choosing an appropriate solid matrix. Metal foams may enable light-weight and durable integrated thermal protection system (TPS)/cryotank systems, thus helping to achieve lower cost of delivering payloads to orbit -- one of NASA's primary goals. Successful development of metallic foams suitable for both TPS and cryogenic applications may be the enabling technology for a truly integrated system because only metals have demonstrated the combined features of: compatibility with the temperature environment, resistance to hydrogen permeation and leakage, and high elongation, needed for strain compatibility of an integrated system. The conceptual studies will guide the development of the foam so that the materials development will stay focused on space transportation needs. Metal foams may well have many spinoff applications as a ductile, robust insulator. One example which has already been identified as a good candidate for structures containing porous metals is an integrated TPS/cryotank structure for use in reusable launch vehicles (RLV).

7. Bamboo Structure

Bamboo is an interesting structure because of its strength and flexibility. It is used extensively in other countries as scaffolding and as construction material. Technical information in the literature is scarce [1]. The fine structure of bamboo fiber consists of several alternating thick and thin layers of microfibrils with different orientations. The fiber matrix interface has lignification and density gradients which account for the strength and toughness of the bamboo. Previous work done with glass fibers and epoxy to mimic this microstructure resulted in 18% lower strength than a non-biomimetic design, while increasing compression strength. Proposed work here is to incorporate carbon nano-tubes into existing, commercially available liquid crystalline polymers. The polymer and nanotubes should co-align in a flow-field to provide a toughening mechanism. Polymer chemists with liquid crystalline expertise and composite engineers will be required for this activity. This work may be incorporated into the Lightweight Composites Activity.

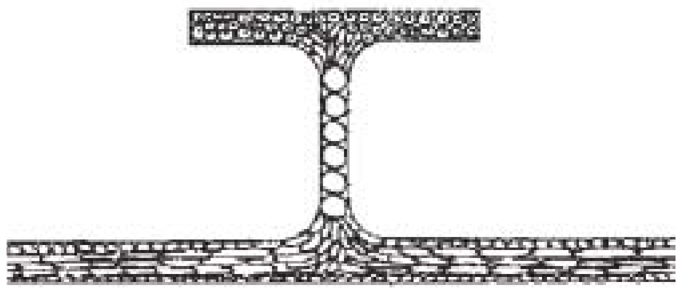
Literature

1. Zhou, B. L., *Materials Chemistry and Physics*, **45**,114-119 (1996).

8. Functionally Graded Metals

Bones and shells exhibit highly ordered, hierarchical structures with very specific orientations and properties for the shape, geometry, and applied loading conditions. Metallic structures can be fabricated to simulate this highly ordered microstructure within a monolithic structure.

The objective of this proposed work is to develop metallic structures using advanced laser deposition techniques to tailor microstructures, properties, and alloys to the structural design. Initial work will require exploring laser deposition techniques and alloy selections to attain ordered microstructures and graded alloys from one material to another within a single structure. The next step is to develop in-house laser-deposition capability for fabricating complex near-net shaped metallic structures. Coupons can then be fabricated for testing and evaluation of material properties and microstructures. The structures will be designed and analyzed to take advantage of oriented properties from functionally graded microstructures and alloys. The localized reinforcement will be examined to selectively increase properties in specific structural regions after which subcomponent panels for testing and analysis can be made.



Functionally graded metals will result in increased structural efficiency, decreased weight, and simplified parts. Near-net shape reduces the weight and increases the strength by reducing the number of joints, and also results in a lower part count which significantly reduces assembly and maintenance time and cost.

9. Self-Healing Metallic Structures

Self-healing metallic structures mimic a biotic organism's use of protective skins, its ability to detect small areas of damage such as cracks, and its ability to heal those defects to strengthen the structure and prevent crack propagation leading to failure. To develop new damage tolerant metallic materials and structures that stop or "self-heal" fatigue cracks, the activity must start with the identification of material systems and processes for advanced concepts. First generation concept is the development of advanced clad materials that inhibit fatigue crack growth. Modifying the clad microstructure should increase crack closure. Increased crack closure will reduce crack-tip driving force and thereby retard fatigue crack growth. Other concepts will be identified and evaluated as part of this research effort. Various 3-D finite element elastic and elastic-plastic analyses of advanced concepts involving multiple materials and multiple interfaces will be performed. Prototype material(s) based on fatigue crack growth analysis code 3-D FASTRAN will be designed. Concept(s)/processes will be downselected and prototype material(s) (coupon level) will be produced. Proof-of-concept fatigue tests will be performed at coupon level and concept(s) will be evaluated to determine feasibility and scale-up. 3-D FASTRAN prototype design needs to be validated based on coupon test results and 3-D FASTRAN will be modified as required. Process will be scaled up with industry partner. Large panel fatigue tests will be conducted and 3-D FASTRAN will be validated based on large panel predictions. Recommendations for commercialization will then be made.

"Healing" materials increase the safe life (reusability) of airframe, launch, and space structures by reducing the propensity for wide spread fatigue damage and thereby reducing the life-cycle costs of aging structures. "Healing" materials will increase the fatigue life of the airframe tenfold by mitigating the growth of small fatigue cracks in structural metallic materials. The first generation concept modifies the properties of the clad used on structural aluminum alloys. A "healing" clad material will have near term benefits; modifications to the clad (a non-load bearing material) will not require a design change for implementation onto existing aircraft designs. Long term benefits will occur through durable ultra-light weight metallic foil structure. The theoretical background for this work has been developed under the aging aircraft program.

10. Growing Structures

Many future space missions are being studied that involve very large space structures such as telescope mirrors, solar concentrators, reflector arrays and human habitats. The size of the structures prohibit them from being launched in a single launch vehicle and therefore will require assembly on orbit. Intelligent structural components that can assemble themselves into a backbone structure for space missions would allow for autonomous assembly and maintenance of the structure. The structural components would also be identical in shape and function so the structure could easily be maintained or replaced. Cost and ease of assembly of the large structures would be realized through this approach.

These structures mimic coral, whose life cycle revolves around finding, attaching to, and ultimately sacrificing itself to form the structural foundation (reefs) that support whole diverse ecologies of other sea life. The intelligent structure can locate and place itself in the larger vehicle structure, analogous to the coral providing the backbone for spacecraft.

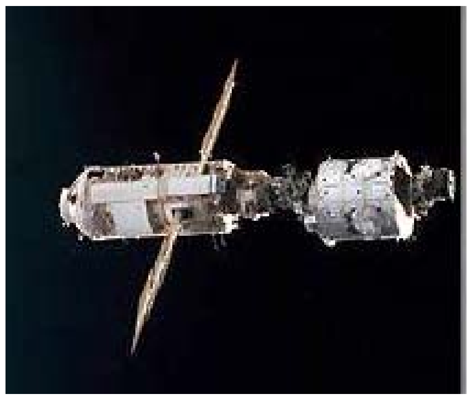
The concept of intelligent structures for on-orbit assembly was developed by John Mankins of NASA Headquarters. Neville Marzwell of JPL has proposed that a team from JPL, MSFC, and LaRC would evaluate potential missions, define a structural concept and design, and fabricate simple engineering units for demonstration of concept. Structures and materials engineers from LaRC and Controls engineers from JPL and MSFC's Manufacturing and Technology Center can work together on this project. Potential applications for this work are in Space Station growth, Lunar and Mars human exploration, Planet Finder, and Planet Imager missions.

11. Regrowth and Repair of Composite Structures

Aircraft and Spacecraft are designed to meet load-carrying requirements based on damage which could occur during the vehicle's life. Economics and safety considerations dictate that aircraft must be able to sustain significant amounts of damage without losing significant load-carrying ability and damaged regions must be repairable. Repair time, outside of scheduled maintenance activities, can be time-consuming and expensive and therefore should be minimized. Spacecraft are not always in an environment where repairs can easily be made. A method which would allow a vehicle to repair minor damage itself could be useful in preventing the propagation of damage and in avoiding costly down time. This approach would improve the safely of the structure as well as make it more economically efficient. However, addition of this mechanism might add so much of a weight penalty as to be impractical.

Animals and plants repair themselves when minor damage is sustained. Bones knit back together after fractures and can return to load-carrying ability as high as they originally could withstand. Bones and other natural structures are dependent upon a mechanism to detect the damage and then a way of moving the necessary nutrients to the damaged region. In a biomimetic system, a resin could be transported to the site of the damage and a way of rebonding fibers would have to be developed. This concept has been shown to work in biomimetic concrete [1].

This would be a combined structures and materials effort. Engineers involved with detecting damage, with the chemistry of fixing the damage and with testing the strength of the repair would be needed. A great deal of small scale manufacturing, analysis and testing would be needed. We would want to have some university people on board who know bone and muscle regenerative mechanisms and limitations. The technique could be applied to any air or spacecraft made from composite material.

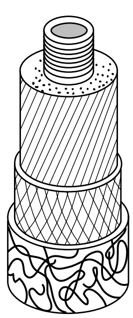


Literature

1. Dry, C. M., "Design of systems for Time Delayed Activated Internal Release of Chemicals in Concrete from Porous Fibers, Aggregates or Prills, to Improve Durability," http://www.arch.vt.edu/Caus/dry.htm.

12. Efficient Tailored Wings and Tails

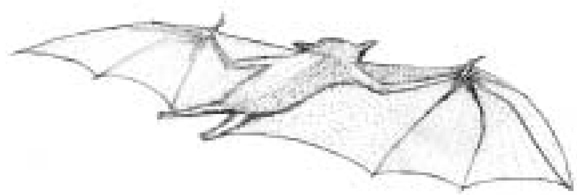
The wings and tail(s) together can make up 50% of an aircraft's weight. Reducing this weight reduces the fuel consumption for a given mission and therefore reduces the CO_2 emissions. There are several ways to reduce the weight of the wing and tail structures: 1) fabricate from lighter material such as a composite 2) tailor the structure to meet anticipated loading conditions and reduce excess weight 3) improve the efficiency by increasing the aspect ratio of the wing 4) reduce the thickness of these structures to improve aerodynamic performance.



Tree fibers

CO_2 emissions could be reduced by 15% by going to an aspect ratio of 15 rather than the aspect ratio of conventional aircraft of less than 12. By reducing the weight of the wing and tail by 35%, $C0_2$ emissions could be reduced by another 6.8 %. Taken together and including the system effects associated with lighter wings and therefore lighter engines, a reduction in CO_2 emissions of 24% could be achieved.

Bird wings are not made from isotropic materials or held together with fasteners, but are constructed of a combination of layered soft and hard materials. Bones are tailored to the loading conditions in ways conventional aircraft are not. Even advanced composites currently used are simple compared to actual bone, muscle, tendon and skin. Trees have fibers in numerous directions and are adaptable to wind conditions in ways man-made structures are not. In addition, birds do not hold their wings stiffly when they fly. An active control system which could adapt to changing flight conditions could improve maneuverability and reduce weight by making the wings more efficient.



We can build off work done under the AST/ACT and HSR programs as well as numerous other programs the Center has been working in the last few years. This would be a major project with many people and a lot of money to take it to completion. However, useful work could be done in the few years for fewer dollars to develop the ideas and run some small scale tests. University researchers with knowledge of bone microstructure will need to be consulted.

13. Puffer Structures

Inflatable space structures are an ongoing area of research. By improving the membrane structure, making it more elastic, more flexible, easier to inflate or more reliable, improved space structures could be built.

Puffer fish inflate to a much greater size when threatened by sucking in air or water. Arteries and other body parts have elastic membranes which inflate or deflate as needed. The materials which allow this membrane elastic behavior would be evaluated to determine what characteristics allow the membrane to inflate and deflate. Biologists will have to be consulted to aid in the characterization. Information gathered from this stage can then be used by materials researchers as inspiration for the development of new materials having the similar characteristics and which can be adapted to the space environment. Requirements and ways of using these materials would require structures and systems engineers.

14. Energy Absorption via Quills

The survivability of a plane or automobile crash is often dependent upon how much energy from the impact is absorbed by the vehicle and how much is passed on to its occupants. If the vehicle crumples or breaks, less energy is left to be absorbed by bone and muscle. In airplane crashes, one way of minimizing injuries is to allow the seats to collapse, which can prevent spinal and other injuries to the occupant. Porcupine quills are hollow tubes which absorb energy, allowing the animal to fall or roll without injury. If some characteristic of these quills could be applied to aircraft seats, fewer people might be injured in plane crashes. In addition, spacecraft designed to return samples from Mars or elsewhere might also be able to take advantage of results of this study.

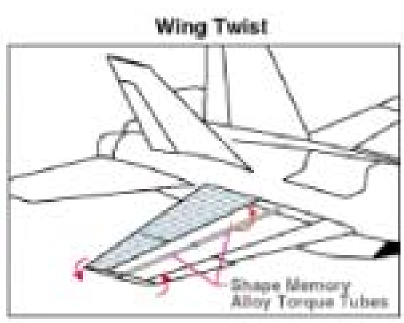
We would be examining the material, construction and mechanism that the quill uses with the help of biology consultants, to determine if any of these could be applied to advance our methods of construction or the materials used today for aircraft seats.

There have been studies at LaRC on survivability of plane crashes and using composite materials as ways to minimize injuries. This study could build on that work. We have structures and materials expertise here that could be used. Since the objective of this research is to save lives, funding could come out of the safety initiative. However, the results of this research would be applicable to all types of aircraft and possibly other vehicles as well. Projects such as Mars Sample Return involve spacecraft designed to impact on landing might also benefit, and therefore fund this effort.

15. Embedded Sensors Long Term Effects

Smart structures require feedback to operate efficiently and effectively without a human guiding every motion. To take advantage of a feedback system, we need to have some method of embedding sensors into a structure which will not significantly reduce the ability of the structure to carry load, will not degrade with time and will provide an adequate amount of feedback information.

Although several types of embedded sensors are currently available, more work needs to be done to determine what sensors work best under what circumstances. This study could include effects of manufacture methods on the sensors. Sensors embedded in a composite would have to survive the curing of the resin, which may occur at high temperatures, as well as operate under all ranges and conditions which the vehicle would encounter during flight.



Animals use feedback from all parts of their bodies to walk, swim or fly. If the nerves in a body deteriorate, the ability of the animal to move reliably or to recover from a misstep diminishes dramatically. An extensive feedback system is the first step toward building autonomous probes, robots, aircraft or spacecraft.

There has been work here on embedded sensors, but more work needs to be done to look at long term effects and evaluate different types of sensors. Materials scientists would be needed initially including NDE people and manufacturing specialists. Structures people would be needed to evaluate the effect of various sensors and controls, and systems engineers would be needed for system integration.

This work could be woven into any program aiming at improved, semi-autonomous vehicles or parts of vehicles. This work would be applicable to aircraft and spacecraft.

16. Smart Structures for Aerospace

We would continue work in this area and build on what has been done. The Aircraft Morphing Program is aligned with Pillar One: Global Civil Aviation, and the fifth national goal of reducing the cost of air travel by 25 percent in 10 years and by 50 percent in 20 years. A primary goal of the Aircraft Morphing Program is to increase the efficiency of aircraft while simplifying aircraft systems and making airplanes easier to produce and maintain. Much of the weight and manufacturing cost of airplanes is in devices that move, referred to as actuated control surfaces. We are looking at new ways to control the flow over aircraft wings in a more efficient and low-cost manner. The Smart Wing project applies new smart materials to twist and bend airplane wings during flight to morph the aircraft shape to one that is optimal for different flight conditions. Conventional aircraft are controlled by rigid structures supported on hinges. These surfaces deflect airflow to control the motion of the aircraft, and can be made more efficient because the flow over the wing cannot abruptly change direction around the corners created by such hinges. In addition, hinged devices are driven by hydraulic systems which add to the cost and the complexity of an aircraft. Smart materials are being used to gently bend and twist the wings, which is more like what birds do to control their motion when they fly. Rather than using motors or hydraulic systems to deflect these hinged surfaces, the smart materials are more like muscles which are distributed throughout the wing structure. They become an integral (or embedded) part of the aircraft structure, which makes them more reliable and less costly to maintain. A smart material is one which can change its shape in response to an external command.

A special nickel titanium alloy known as a Shape Memory Alloy (SMA) can be trained to remember a specific shape, which it changes back to when heated by an electric current. If a wire of SMA is stretched, it will grow to a new, longer length. When it is heated with an electric current, it will shrink back to the original, shorter length that it was trained to remember. This is similar to the way a muscle works when it is stimulated by a nerve impulse. By arranging these smart materials in a push-pull fashion, different parts of an airplane structure can be actuated, or made to move. Several smart concepts are being studied in this program. The first concept uses tubes of SMA material to twist the wing from root to tip. Four-inch long SMA tubes were manufactured using special machining processes and trained to twist (or produce torque) when heated. Thus the tubes are referred to as torque tubes. The torque tubes were attached to stainless steel shafts that were placed in the center of a wing. When the torque tube is actuated, the flexible wing structure twists along its span. This action increases the angle of the tip of the wing, thereby increasing the lift force on the wing. The structure is designed so that when the torque tube cools, the wing returns to its previous shape. In total, two SMA torque tubes were used in the smart wing. The torque tubes twisted the wing 1.25 degrees and increased the ability of an aircraft to roll by 8%. The second concept is called a hingeless control surface. SMA wires or tendons are stretched, and then embedded in the top and bottom surfaces of a flap. When electric current is applied to the SMA tendons on the bottom of the wing, those tendons shrink and bend the surface downward. Electric current applied to the SMA tendons on the top of the wing bend the surface upward. The system is designed so that if power is not applied, the flap remains in a neutral, or undeflected configuration. Tests of the hingeless surface showed an 8% increase in lift over conventional wings. The Smart Wing project is jointly supported by the Defense Advanced Research Projects Agency, NASA Langley Research Center, Air Force Wright Laboratories, and the Naval Research Laboratories. DARPA funding is supporting the prime contractor, Northrop-Grumman and subcontractors including Lockheed Martin Astronautics and several universities and small companies. Two 16%-scale F-18 E/F wing models with embedded smart structures were built and wind-tunnel tested in the NASA Langley 16-foot Transonic Dynamic Tunnel. Smart structures and materials technologies that can twist or bend a wing on command will provide innovative capabilities to future military and commercial fixed wing vehicles and rotorcraft.

17. Biomimetic Approaches to Damage Tolerance: Improved Load Paths Near Stress Concentrations

The fiber direction in the trunk of a tree is oriented along the tree's major axis except in locations very near stress concentrations, such as the interface with branches. At these locations, the wood fiber direction is modified to effectively carry load around the branch, thus reducing the local stress concentration. This redirection also allows for more efficient load introduction from each branch.

In traditional composites manufacturing, holes are introduced in laminated composites by cutting through the loaded fibers resulting in free edge stresses which tend to induce delaminations. Similar edge stresses and delaminations tend to occur at the interface between skin and stiffener flanges, notches, and other discontinuities.

By studying the efficient load paths of trees, fiber orientation may be improved to reduce or even eliminate the problem of load paths near discontinuities in composites. A small amount of work was done in the late 1980's to develop molded holes in composites. It appears that two factors contributed to the lack of acceptance of the concept. First, the manufacturing costs associated with molded holes were prohibitive. Second, the fiber orientations near the holes did not produce an optimum load transfer particularly at small hole diameters.

This work will build on the manufacturing advances in weaving, braiding and tow placement developed during the NASA AST program to address the deficiencies mentioned previously [1-4]. The work will also develop a rigorous biologically inspired combined damage tolerance and optimization approach that will be used to design composites for optimum load transfer around discontinuities of many types including holes, notches, and skin and stiffener flange interfaces. The configurations will be tested to validate the analysis and design. Workforce with the following skills/knowledge will be required: Stress analysis/damage tolerance, optimization, composites manufacturing and biology/botany.

Literature

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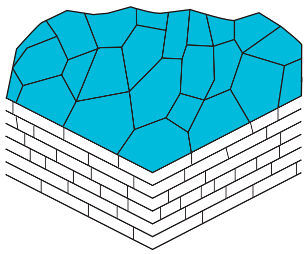
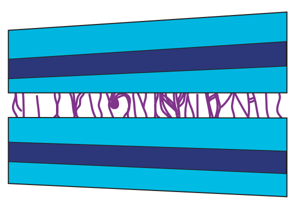
4. Fierling, Y. P. H., "Analysis of Fiber-Reinforced Composite Plates Utilizing Curvilinear Fiber Trajectories," M.S. Thesis, Engineering Mechanics, Virginia Tech, May 1995.

18. Biomimetic Approaches to Damage Tolerance Toughening Methods for Textile Composites

Mollusk shells are formed by combining strong brittle inorganic materials with tough organic materials. The failure stresses of the inorganic materials approach 20 ksi while some of the organic elements have been observed to stretch up to 1000 percent without damage. The combination of the two materials makes a shell that is both strong and tough. For example, a tortuous crack path is required for a through crack to grow at plate interfaces resulting in increased energy required for crack growth. Also, fibrils of tough ductile organic matrix material may bridge cracks in the strong inorganic material. These mechanisms significantly increase the fracture toughness of the shells. A biologically inspired structural material system might contain 90% carbon yarn for strength, 8% in-plane toughening material and 2% out-of-plane toughening material. The examination of biological structures will help to identify the appropriate toughening materials, material density and architecture to produce tougher material systems while retaining the required in-plane strength.



Textile manufacturing techniques developed under the AST program can be used to form composites consisting of combinations of strong materials to carry load, tough materials to contain damage, and discrete through-thickness reinforcements (stitches) to reduce delaminations. Some work has been done in the past to manufacture, test, and analyze toughened materials. For example, the newly developed AST textile manufacturing technologies make it possible to produce large quantities of toughened material with a minimal increase in expense compared with untoughened materials. However, even with these advances in manufacturing, little has been done to determine the best toughening materials or toughening material architectures. Rather, material and architecture have been driven by manufacturing concerns and the mechanical properties have often come as byproducts.



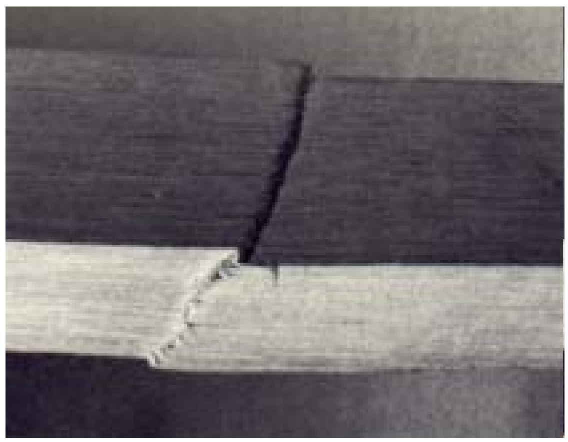
Biological structures such as mollusk shells will be examined to determine the reasons for their considerable strength and damage tolerance. The mechanisms discovered from the biological systems will be mimicked in material architectures. A rigorous analytical approach for damage tolerance analysis will be developed. Once the appropriate reinforcement materials and architectures have been identified, candidate material systems will be manufactured and tested.

Damage containment is critical to the success of many composites structures programs. The work that is proposed will use the lessons learned from the study of biological systems to help determine the most suitable materials and architectures to contain damage in highly loaded structures.

19. Kink Band Formation

The mechanisms involved in the compressive failure of unidirectional composite materials and wood are very similar. It would be prohibitively costly to have composite material samples manufactured with widely varying microstructures. Nature has provided woods of diversely varying microstructure. Samples of different species of wood can be obtained inexpensively, their microstructure characterized and compressive tests parallel to the grain conducted. Understanding of the structure-property relationship for the wood samples could guide Langley researchers in developing man-made composite material with high compressive strength or good energy absorbing capabilities.

This study could also be extended to plywood constructions of the differing wood species and the study results extended to practical composite laminates. Even the structure of some woods vary widely within the same species. For example, the density of balsa can vary by a factor of seven. By including a range of balsa densities some experimental parameters could be controlled while parameters such as cell wall thickness could be examined. This study might address issues such as the optimum diameter and distribution of fibers in a fiber reinforced composite material.



This work would be applicable to any structure built from composite materials and would be a good way to look at microstructures and evaluate which ones we could copy for our own uses. We have structures and materials researchers here who could do most of this work, but we might want some advise from someone familiar with wood such as from Virginia Tech's Forest Products and Wood Science program or the Forest Products Lab in Wisconsin.

C. Guidance and Controls

1. Biomimetic Image Processing and Vision Systems

Information in the form of images is central to the navigation, foraging, and ultimately the survival of many animals. Man-made devices for the acquisition of images are well developed, and in many cases superior to nature. However, the processing and interpretation of this data is primitive by comparison, and quickly stress even the most advanced computer systems. This work looks to nature to find novel methods for the processing of data, and the design of imaging devices that implement this processing.

Natural systems excel at the complex and data rich task of image processing and interaction. If even some of this efficiency can be imparted to mechanical counterparts, the impact would be profound and find widespread application. Several areas of potential improvement are:

a) The "Signals-to-Sense" Problem: The eye-brain must tame the very wild variations in pattern, lighting, and color, and turn physical radiometric measurements into symbols/words, skeletal forms, and scene descriptions. This transformation of the photons into information is probably far more difficult than "intelligence" (reasoning from well defined starting data). The combinatorial mathematics of even small regions of image space are explosive, and become astronomical for larger regions and image frames.

b) Local Preprocessing: A major feature of natural vision is the retina being a part of the brain, sent out as an outrigger during fetal development to the eye. Apparently vision is so difficult a group of tasks that the brain must send part of itself out to the "sensor" and do a great deal of "focal plane processing" to achieve the higher level tasks of the cortex proper.

c) Multifunction Architecture: The natural scheme of computing vision displays many aspects of elegance. One computation or sensory signal performing multiple functions at once-- modular overlapping parallel processing. Major divisions are "what" (object recognition in inferotemporal cortex) versus "where" (spatial location and layout in post-parietal cortex). Respectively, these regions are "under the ear" and "above the ear near crest of cranium".

Previous work on the Retinex Image Processing System produced an algorithm that improves color consistency in a broad class of images. Retinex was motivated by studies of natural image perception in human sight. This effort would build on Retinex experience, but be a longer term and broader research effort into natural image perception.

2. Cooperative Guidance Algorithms for Intelligent Swarms

There are examples in nature, such as in bee hives and ant colonies, where a large group acts collectively to accomplish a task, but does so with very limited central control and communication. In a similar manner fleets of vehicles, either airborne or ground based, can be employed to accomplish large scale tasks, while providing fault tolerance and flexibility. Although hardware requirements differ greatly among different implementations, a common component to the development of these types of systems is guidance algorithms that can translate the high-level system behavior into low-level stimulus and response actions for individual elements. This work involves analysis of the behavior, and development of a set of logical rules that the agent can employ to determine its course of action. A key aspect here is analysis of the resulting behavior as a system of interacting dynamic elements, rather than of the response of an individual.

The starting point for this work is to review existing literature on cooperative guidance algorithms and existing software tools for multi-agent simulations. From these sources a research effort will emerge which defines the structure of guidance algorithms for vehicle based multi-agent systems.

There are many applications for which this design method would be beneficial. Some examples are:

a) Exploration: The use of coordinated groups of simple single-sensor rovers for planetary exploration offers many advantages. The system provides a broader and more effective search than a single rover with a suite of sensors, and also ensures fault tolerance by avoiding a single point of failure.

b) Reconfiguration: High bandwidth communication, which typically requires a large antenna, could be accomplished by an array of robots which would arrange themselves into a phased-array antenna, transmit the data, and then return to being roving data gathers.

c) Transportation: Intelligent highway and air transport systems could make use of automated lead vehicles and guidance algorithms designed to emulate natural flocking behavior in birds and fish. This would ensure safe vehicles spacing, but not require a centralized control system.

Fundamental skills for this effort exist, however, it would not be an extension of previous work and so would involve time coming up to speed. Personnel from the Guidance and Control Branch with possible contract support can do this work.

3. Dynamics and Control of Biologically-Inspired Flight Systems

Insects and birds command a flight range and maneuverability which is unmatched by mechanical counterparts. This work seeks to understand and imitate that ability. Understanding and controlling the flight dynamics of bird and insect scale vehicles provides for a new class of aeronautical systems, with applications in military reconnaissance, planetary exploration, and industrial robotics.

An initial effort in this area would include:

a) Low Reynolds number testing of flapping and flexible wing models, to develop an aerodynamic database which reflects flight conditions of birds and insects.

b) The development of CFD predictions for these systems, and the design of approximate aerodynamic models.

c) Analysis of power requirements, and control/instrumentation complexity for flapping flight micro-air vehicle.

Fundamental skills for the analysis and mechanized experiments exist, however, we would rely on outside research to provide detailed information on the flapping motion of various birds and insects. Personnel from the Airborne Systems and Aerodynamics Competencies need to collaborate on this activity.

4. Genetic Algorithms for Adaptation and Design of Multi-Agent Systems

Very simple reactions involving a large number of interacting agents can yield impressively complex behavior. Biology is rich with examples of this process, from the action of the immune system to the swarming of bees. In these cases the system performs actions which are beyond the ability of the individual and the difference in not just one of scale, but also of type. Directly designing these low-level reactions in order to generate useful system behavior, however, is difficult if not impossible. For example, iterating over a simple non-linear equation can yield a fractal image that resembles a tree, but reversing the process to find the equations which reproduce a specific image of a tree is very difficult. Nature addresses this design problem though evolution. This work looks at the use of genetic algorithms, which apply breeding, mutation, and natural selection in software, to the design multi-agent systems.

Several applications exists which would benefit from this work, some examples are:

a) Cooperative Robotics: A group of planetary rovers is given the task of searching for concentrations of frozen water in quantities large enough to hold evidence of past life. A genetic algorithm tunes the prospecting strategy using data from other sensors to determine correlations that were unknown when the mission was planned.

b) Design Optimization: A spacecraft system has a large design space, with many tradeoffs in terms of mass, cost and performance. Through genetic algorithms, individual agents evolve strategies to explore this design space, define feasible regions, and using simulation software evaluate the performance of resulting designs. An anticipated success would be a design strategy which reduced spacecraft mass by combining component functionality in a non-obvious way.

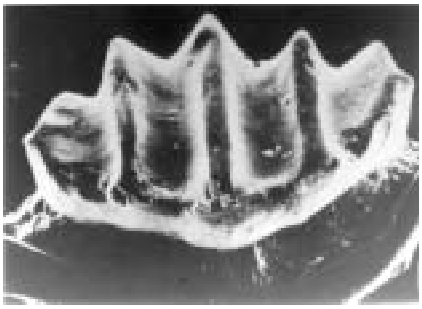
c) Unstructured Data Mining: A deep space or planetary probe may collect more data from its sensor system than it can transmit back to earth. Software agents evolve search strategies and compete with one another looking for causal correlations in the data. The data deemed most interesting is transmitted back to earth, along with the search strategy which "discovered" it.

The starting point of this work would be a review of existing literature and available software for multi-agent systems. Some previous work with genetic algorithms could be tapped to support this effort.

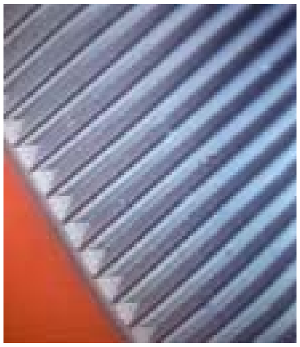
D. Aeronautics

1. Turbulent Drag Reduction

It has long been known that certain marine animals possess unique morphologies thought to reduce drag. The most famous example of this is the skin structure of certain fast sharks. The dermal denticle structure of shark skin contains tiny grooves aligned with the flow. A series of experimental wind and water tunnel studies showed that engineered grooved surfaces of the same scale as the shark dermal dentical structure reduced turbulent skin friction 6% to 8%. While the experimental work was done independent of the knowledge of shark skin structure, the clear lesson learned was that biological systems should be studied for other possible drag reduction morphologies.



Shark skin



Engineered grooved surfaces

A logical research plan would be to investigate certain marine morphologies such as leading edge bumps, shark tips, fin-body fillets, and afterbody grooves. Simple models containing the simulated geometry would be fabricated, and a series of screening tests would be conducted in a low-speed wind tunnel to measure flow field characteristics and possible drag reduction mechanisms. This kind of testing is routinely done in FPCB using any of a number of available low-speed tunnels and standard measurement techniques. Based on these initial screening tests, further testing would be done on promising configurations at higher speeds (higher Reynolds numbers) using advanced flow field diagnostic tools.

Computational studies (validated using the experimental results) would be used to to narrow the parameter space of the experimental investigation and to examine off-design performance.

In the future, highly efficient aircraft will be required to meet noise and emission goals. Even a few percent reduction in skin friction drag or induced drag could be important in meeting these goals since lower drag translates into smaller propulsion units and less fuel consumption/lower emissions.

No formal drag reduction program exists at LaRC at this time. However, the base research program does contain a flow control sub-element, which would naturally encompass this proposed work.

2. Flapping Wing Flight

Although fixed wing aircraft are a logical solution to the problem of flight at large-scales, it is not entirely clear that it is the best solution for small-scale vehicle flight. No fixed-wing aircraft can match the maneuverability and agility of a bird or flying insect, and we are still far from a complete understanding of the unsteady aerodynamic mechanisms at play in flapping wing flight. In addition, regions of unsteady flow exist in a number of places on conventional fixed-wing aircraft (e.g., high-lift systems, forebody vortex shedding), and an understanding of these unsteady flows on biological systems may lead to innovative ways of utilizing those mechanisms to some advantage in an engineered flight system. Therefore, it is important to study the unsteady aerodynamics of flapping wing flight to not only develop the capability to design small-scale flapping wing vehicles for stealth and surveillance in military applications, but also for possible application to the control of unsteady flows on conventional aerodynamic vehicles.

One of the initial problems associated with flapping wing flight is the scarcity of good flow field measurements and limited computational support. Typically such work on live biological subjects is conducted by experimental biologists with limited resources (instrumentation/wind tunnels/computational tools). A serious effort to understand flapping wing flight will require a multidisciplinary team of aerodynamicists and biologists to 1) identify the unsteady phenomena to be studied, 2) to develop experimental models and instrumentation to investigate these phenomena, and 3) to develop the computational tools required to compute unsteady flows. The experimental data will be used to validate the computational tools, and the computations will then be used to predict the performance of subsequent engineered systems (i.e. small-scale flapping wing vehicles, and improved understanding and control of unsteady flows on conventional vehicles). The experimental and computational skills required for this work already exist in the AAA Competency. The existing ornithopter effort (FY 00 funding from the LaRC base program) would be the logical “home” for this effort.

3. Long Endurance Flight

Soaring birds utilize the dynamics of the atmosphere to minimize the energy expenditure required to stay aloft. The most obvious example of this is the use of thermals to gain altitude, a technique not unknown to sailplane enthusiasts. But beyond this, birds also appear to utilize localized small-scale shear layers, strong prevailing winds, and organized group behavior to travel long distances or to stay aloft for extended periods on a minimum of fuel. Exactly how they locate and sense these atmospheric changes is unclear, but everyone is familiar with the V-formations of migrating ducks and geese. Also, any observation of seagulls windsurfing just off a beach or maintaining control in high, gusty wind conditions brings a new appreciation of their ability to find and use the dynamics of the atmosphere to their advantage. A few innovative aerodynamicists are now suggesting that "super efficient" long endurance flight may be possible for smaller-scale aircraft (UAVs for sensing, data relay, etc.) by incorporating innovative low drag designs, coupled with advanced sensors, adaptive wings, advanced control systems, and utilizing formation flying techniques similar to biological systems.

The current proposal would initiate a combined aerodynamics/experimental biology/structures/materials/ controls/sensors team of researchers to identify techniques used by soaring birds to enhance lift/reduce drag/extract energy from the atmosphere and remain aloft for extended periods of time. Flexible wings structures designed to twist and warp under varying loads combined with smart sensors for sensing local flow conditions and organized group behavior to minimize drag would be studied for possible application to UAV design. In addition, drag reduction morphologies would be investigated as well as active separation control techniques used by birds. The skills required for this work exist in-house, except for experimental biology, which may be obtained through grants or contracts. Low-speed tunnels could be modified to provide typical unsteady flow conditions for the initial experimental work.

The ultimate goal of this work would be a long endurance, semi-autonomous macro-UAV (perhaps something with a wingspan on the order of 1 – 10 meters) that could function alone or in groups for data gathering and data relay. This activity would be distinct from the DARPA micro-UAV effort, which is concentrating on very small, centimeter-sized aircraft for stealthy surveillance. Presently, macro-size UAVs are used for weather and atmospheric science sensing as well as for some data relay functions. Current designs suffer from limited endurance, limited range, low speed, and in some cases, fragile construction. However, the most severe limitation of current designs comes from the fact that operations are confined to uninhabited land areas or over oceans. Reliable designs are needed that can be certified for national airspace. Being able to operate in populated areas would allow a host of new functions for such vehicles, including telecommunications, utilities monitoring, pollution sensing, search and rescue operations, traffic information and control, as well as corporate and civil security. In rural and remote areas, such vehicles could serve to aid border patrols and coastal surveillance, as well as agriculture needs. In fact, these vehicles could be useful anywhere local or regional information is required at a cost substantially below the cost of satellite data. Information published in a joint AUVSI/FAA (Association for Unmanned Vehicle Systems International/ Federal Aviation Administration) report issued in 1998 (http://www.auvsi.org/auvsicc/faaisg/faaisg.htm) indicates that the weather and atmospheric science community needs approximately 1,000,000 UAV flight hours per year over the oceans alone. This same report estimates that the aerostat market for telecommunications will be $7-10 billion annually by the year 2015 (or approximately 2% of the satellite market. Of course, an application unique to NASA would be for remote planetary atmosphere exploration using small, lightweight, multi-functional swarms of these devices to cover large areas and to operate cooperatively.

Research in drag reduction, autonomous control, advanced sensors, lightweight structures, and advanced materials could all be applied to this area, and using a biomimetic approach may help solve some of the current limitations of UAVs and hasten the growth of this emerging market. This would be essentially a new research area for Langley but would rely heavily on existing skills. Reference AI6 gives a more detailed review of many of the issues related to biomimetically-inspired UAVs.

E. Biomimetic Systems

1. Autonomous Laser-Based Mobile Units

Laser beams can be used to perform many functions on metals that cells perform within a body. Laser beams can be used to deposit new material, detect flaws, repair (weld) flaws, and remove material. These functions are all similar to those performed by cells within a body the way proofreading cells check and correct DNA strands, phagocytes consume invading cells, or bones remodel. A small army of autonomous laser-based units equipped with self mobility and communications for interacting and coordinating actions could work on the inside or outside of a spacecraft to build, monitor health, repair, and change the structure as necessary for the mission. If the composition of surrounding materials are conducive to laser deposition, structural material could also be excavated from the extraterrestrial environment for fabrication of structures on other celestial bodies.

The objective of this work is to develop autonomous mobile units with laser capabilities for depositing and removing material, detecting flaws, and repairing these flaws all using different settings with the same type of laser. This activity would require a multidisciplinary approach which can be worked in parallel to develop autonomous mobile units and analyze resulting materials. The work would involve evaluating laser-interactions with materials, non-destructively evaluating structures and welding or repairing flaws as detected, all using different setings with the same type of laser. Samples will be fabricated using laser processes for metallurgical characterization and property testing. Structures will be designed and analyzed for efficient, compact packaging of laser, power, supply materials, communication guidance and control and mechanisms for mobility. Lasers will need to be developed to increase power output and efficiency, and miniaturized to reduce the size of these autonomous units. Other possible uses of lasers on small mobile units will be assessed. Guidance and control systems need to be developed for communication between units so they can navigate around a structure and work cooperatively with or independently of other units.

This will have to be a multidisciplinary effort involving skills from S&MC, SEC, AAAC, and ASC at LaRC. Involvement from SMC would include MTSB for materials and process development, testing, and analysis, MDB for materials durability analysis, structural design and testing, NESB for non-destructive analysis for flaw detection, and ATTB for technical support. Collaboration with other competencies will also be required: SEC - LSB for laser processing development, AAAC - ISDB, AMDB for systems integration and from ASB - GCB and SIB for communications and controls between units.

This idea would create a new ability to build and maintain spacecraft in space. Implementation of autonomous laser-based mobile units will extend the life and significantly increase the flexibility of structures in space, allowing self-evaluation and repairs without requiring a rendezvous with human interactions. This technology could also be adapted to build structures on other planets using materials excavated on-site. Due to its flexibility, this should reduce costs and weight because a structure can be built for an initial application (such as fuel housings for a disposable launch vehicle), then changed with these units to perform different functions once on orbit.

Portions of the laser-materials interactions currently exist or are being developed under an ASPO workpackage, other portions could be developed independent of an integrated project, but this program would require significant investment and a team approach for successful development.

2. Snakelike Automation for Inspection

Aircraft and spacecraft maintenance involves periodic inspections of enclosed areas which are difficult to examine. Inspections which are not thorough could miss critical flaws causing a safety concern, but inspections are time-consuming, difficult and expensive. The quality of these inspections and the cost and time involved could be reduced by use of a snake-like device which could be programmed to look for certain types of damage, and carry a small camera, ultrasonic device or some other tool. This robot-snake would move through small ports in the craft and maneuver through tight spaces without a human guide and would therefore need to move in a manner similar to the way a real snake moves. The result would be reduced cost and down-time for vehicle inspections reducing operating costs.

Another application would be exploring a rough terrain, such as Mars, in an area where wheeled vehicles could not travel. Robot-snakes could also be sent into fluid and "swim" to explore contaminated water or slither in to do inspections in places too dangerous for humans.

The technology could be applied on several levels: Macro-snakes for planetary surface exploration, mini-snakes for inspection and repair of aerospace structures with limited access, micro-snakes for exploration within the human body (not explicitly NASA's mission, but a good spin-off).

We would be building our own "snakes" which would move like snakes but have a computer controlled brain. This effort would require structures, materials, controls, and systems people available at Langley. Additionally, people who have studied snake locomotion would be needed (biologists or engineers). This project could be funded through existing safety program or any other program interested in improving inspection techniques or an NDE program. Snakes could carry miniature sensors to look for non-visible damage in metals or composites. The work is applicable to aircraft, spacecraft and to any such program with the goal of reducing costs.

3. Brilliant Inspection/Repair Agents

Autonomous Macro-Micro-Nano Inspection and Repair Agents operate as a distributed intelligent capability to assure structural health and provide probability-of-failure data for dynamic risk assessment. Brilliant NDE Agents work with smart structures/materials to reduce load levels while repair is being made and certified. The concept mimics the disease-fighting and wound-repairing systems in the bloodstream. Many Agents swarm around the structure, performing continuous measurements of structural parameters, passing these results on to computational nodes who incorporate them into calculations of remaining structural life and probability of failure (nervous system, brain). When damage is identified, the swarm performs more sensitive and specific diagnostic tests, and then initiates localized repairs. The members of the swarm, especially the micro- and nano-dimensioned ones, might draw energy and raw materials from the structure. This system can have applications to both space-based and land based systems requiring structural health management, including launch and transport vehicles, satellite systems, satellite and planetary habitats. Animation of the proposed system may be viewed at: http://www-nesb.larc.nasa.gov/VIDEO/NDE_AgentHigh.mov.

There is a small effort under the Inherently Reliable Systems program, which is only enough to begin to consider the miniaturization of NDE systems and the development of autonomous approaches to inspection. There is another small program in the Airborne Systems Competency to look at swarm theory and flapping flight for small air vehicles. Other Centers are developing small orbiting vehicles, which may serve as candidate platforms for this type of work. Examples are the Personal Satellite Assistant (ARC), a baseball-sized autonomous vehicle for use inside a space vehicle, and the free-flying AERCam (JSC), a basketball-sized craft containing two video cameras, which has already flown on a Shuttle mission.

The plan would be to try to develop a joint effort with the necessary LaRC researchers and with the telerobotics personnel at JSC, JPL, and ARC toward the goal. To do this properly, the effort will require most, if not all of the Competencies to participate. Examples are S&MC (NDE systems, materials and structures requirements), Airborne Systems (swarm theory, station-keeping, control theory, flapping flight vehicles for earth-based applications), Systems Engineering (miniaturization of mechanical and electronic systems). In addition, it makes sense to team with the other Centers mentioned above to leverage their work already under way. Considering NASA as a whole, there are probably no technological skill gaps. The gaps to be closed may be inter-Center politics rather than technical in nature.

There is a current attitude in the aerospace world that integrated vehicle health management (IVHM) is a necessary part of a successful reusable fleet. Even so, in situ structural sensors will always be somewhat limited, and a need will exist to supplement those sensors with other diagnostics. Also, current structural IVHM does not include repairs, so this proposal could be considered as a generalized extension to IVHM. The appropriate metrics would include improved safety and mission assurance and life-cycle cost savings.

4. Discarding Damaged Areas

Damage to aircraft and spacecraft occurs in its normal use in a normal lifetime. This damage must be evaluated and often repaired to allow continued safe use of the craft. In commercial aircraft this repair may require the plane to be out of service unexpectedly, disrupting schedules and causing expensive delays. In a space environment, damage from micrometeorites could be more than just inconvenient or expensive.   Such damage could force an evacuation from part of a space station and could be difficult to repair. If an extra layer of skin were added that would be shed in the event of damage, some of these problems could be avoided.   The underlying skin would have to be strong enough, and air and water tight on its own to allow the craft to function at or near full capacity. The added weight penalty might be worthwhile if repairs could be delayed until scheduled maintenance times or avoided entirely. Snakes and some other animals molt or shed their skins when growing or when the skin is damaged or old. By discarding a damaged area, a new, undamaged skin could function as well as the original skin..

This would be a combined structures and materials effort with a contribution from controls engineers to help development of the methodology for determining where and when the damage has occurred and how to dispose of it. A great deal of small scale manufacturing, analysis and testing would be needed. The technique could be applied to any air or spacecraft.

F. In-Situ Resource Utilization

1. Proton Collector

One of the difficulties envisioned in the planetary colonization of Mars is the absence of hydrogen in the atmosphere [1]. Hydrogen is required for water and propellant generation. The current plan is to import hydrogen so the astronauts can produce methane and water. This project proposes the use of a material that can act as a hydrogen sponge to collect protons in space and recombine them to form hydrogen. Collecting protons in space may be achieved by using charge transport polymer films. Enough hydrogen may be generated to do something useful with. Preliminary work will be required to check on the proton flux in space.

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2. Plant-like Purification System

Plant root systems are able to act as filtration systems for wastewater treatment. Hyacinths for example, are so efficient at this task that there are some towns that use hyacinths as their main water treatment method [1]. This mechanism in plants can be mimicked for metal recovery and oxygen generation operations and may be achieved by incorporating additives like EDTA into synthetic membranes and spinning fibers with high areal cross section. Filtration would be at the nano level and be like a plant in complexing chemically with impurities. Most of the skills for polymer work exist, but expertise at SEC need to be tapped for device fabrication. Successful prototyping of this purification device will be an enabling technology for the colonization of Mars, and can be useful even in the current mode of space transportation.

Literature

1. Environment, Energy and Resource Management, NASA Spinoffs 30 Years, p. 69.

3. Water Generation

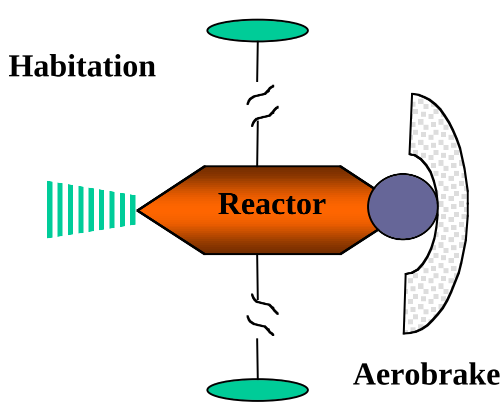
With the successful fabrication of devices from items 1 and 2, there should be sufficient hydrogen (from the proton collector) and oxygen (freed up the the metal oxides in Mars) collected from the space environment so that it's possible to make a device into which these two reactants can be fed. The resulting reaction forms water, providing a source of this valuable resource in a new planetary habitat. This activity is basically a synthesis of two other projects (items 1 and 2) to form a third useful device for the promotion of human survival in a hostile environment. There is some chemistry expertise in-house, but initial work in this project is more suitably performed in an academic research environment through a university grant. The device prototype work can then be performed by our SEC personnel.

4. In-situ Propellant Generation

Propellant is the largest component of interplanetary space transportation vehicles. On the other hand, the planets that might be visited have resources of one sort or another that could yield propellant. As an example, Mars has an atmosphere of CO_2 that can be converted to oxidizer and propellant (methane). A visiting vehicle could store only enough oxygen for the outbound trip, and use hydrogen as a propellant. The return trip could use methane derived from Mars carbon dioxide and the scavenged hydrogen. In addition organic by-products could be generated in the process, which, when used with bio-engineered organisms could provide consumables.

5. Artificial Gravity Tethers

Long missions in space are required to transport humans to even the nearest planets. The most effective propulsion system to accomplish this task is nuclear thermal. In addition, the long space trips are harmful to human physiology due to low gravity, natural environments, and, in the case of nuclear propulsion, the higher man-made radiation environment. The desirable solution is some form of artificial gravity. Spinning can accomplish this, as well as provide some reduction in radiation environment. Unfortunately, structures to accomplish this would represent a tremendous burden on the usable mass carried by the transport vehicle. Light-weight tethers could be developed that provide low-impact, considerable radiation reduction, and artificial-G transportation between earth and Mars.



G. Non-biomimetic, but Biomimetic Enabling

During the brainstorm sessions, it quickly became apparent that whether the issue at hand is biomimetic applications for aeronautics or space, a critical component for the success of biomimetic systems is the availability of efficient power or energy sources. While these energy sources may not be biomimetic, they are biomimetic enabling. The same thing can be said of nanotechnology, some of which is not biomimetic, but which has large impact on the ability to miniaturize sensors necessary to mimic biological systems. The proposed ideas in these areas are outllined in this section.

1. Phase Changes in Materials

As polymers go through phase changes, energy is either released or absorbed. If the amount of energy released or absorbed is large enough and if the phase changes can be controlled to occur when desired, one could utilize these materials for energy storage (or heat sink) and energy generation. The research required would involve increasing the amount of energy phase changes could store, and developing methods to release and absorb the energy on demand. While not biomimetic, this is a biomimetic enabling idea for an energy generation mechanism.

Initial work will require a survey of the literature to determine who is working in the area and how much work is currently ongoing. No work is currently being done here at NASA LaRC. It is assumed there is a limited amount of work being done at the DOD, DOE or Universities.

Polymer/material scientists will be needed to design and synthesize the new materials which have large, energetic phase transitions. Physicists are needed to design and develop methods to release and absorb the energy on demand and to make the process highly efficient so that they are viable in aerospace and other systems.

Goals for this research are: to produce extremely lightweight devices that are capable of storing and releasing high amounts of energy on demand, to make these phase change “batteries” fully rechargeable without any degradation in capacity over time and finally, to develop devices which operate as heat sinks by changing phases with the introduction of heat energy, and, conversely, the release of heat with opposite phase changes.

2. Artificial Photosynthesis

Plants use sunlight to synthesize energy, which is stored chemically. This process may be mimicked by the development of photoactive polymer systems that contain dye molecules with energy storage capabilities. As the energy is used from the photoactive polymer batteries, ground based laser systems could recharge using specific wavelength light for the specific photoactive polymer. This process would use more energetic, tunable laser light to transfer the energy from a ground based laser system to induce changes in photoactive polymer systems, causing them to become capable of storing the energy.

A goal of the research is to produce lightweight devices which act as power sources. These devices would be capable of producing, storing and releasing energy, and of being activated by laser energy. Another goal is for these devices to be fully rechargeable without any degradation in capacity over time. This concept would allow the heavy energy generating source (high power laser) to be located on Earth while the lighter power conversion source would be on an aircraft or spacecraft.

The literature would have to be surveyed to determine who is working in the area and how much work is currently ongoing. No current work being done here at NASA LaRC. Assume there is a limited amount of work being done at the DOD, DOE or Universities. Polymer/material scientists are needed to design and synthesize the new materials which have energy storage and conversion capability when activated by lasers. Physicists are needed to design and develop laser methods to "charge" these materials with energy. Physicists are also needed to develop methods to convert energy stored as a chemical source into a power source with high efficiency.

Research should reside in the Structures and Materials Competency and probably led from the Advanced Materials and Processing Branch, at least initially when new materials development is the major priority. Significant involvement will be required of the Systems Engineering Competency and more specifically, the Laser Systems Branch and the Electro-Optics and Controls Branch.

3. Eel-like Energy Generator

Eels have cells capable of producing up to 600 volts of electricity running the length of their bodies. They do so in a way similar to the way battery cells produce electricity. The eel turns itself into an electric circuit by modifying its muscle cells [1]. Mimicking the way eels generate electricity may warrant investigation, considering that this fish can produce such a large amount of electricity and can control the power output efficiently. At lower power outputs, the device that mimics eels can also be used as a sensor similar to the way weakly electric fish are able to image the electric properties of their environment [2,3]. This work would require the expertise of physicists residing in NESB, aided with a biologist who may be hired as a consultant. Potential applications for this device include energy sources for vehicles which can double as electric sensors of the environment.

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4. Sonoluminescence

The collapse of bubbles during acoustic cavitation can lead to the formation of isolated "hot spots" where temperatures can reach several thousand degrees [1], In fact, scientists recently measured temperatures ranging from 2300 to 5100 K by controlling the heat capacity and thermal conductivity of the gases in the bubbles. The resulting temperature can induce chemical activity in the vicinity of the collapsing bubbles. The potential exists for this energy to be controlled and harnessed as a means for damage repair in resins and composites by an intelligent inspection and repair system. Expertise in physics for this work resides in NESB. The potential application as a mechanism for brilliant repair systems is an area that NESB has expertise in as well.

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5. Nanowiring

Recent work demonstrated that nanowires can be generated by sending two reactants through a small capillary, leaving behind conducting material [1]. This information points to promising methods by which nanowires may be grown in structures to provide a mechanism for intelligent health monitoring and repair. The potential for revolutionary new methods in sensor technology may be exploited using existing personnel with materials and physics know-how currently residing in the S& MC. We may need to fill a skill gap in nanofabrication to accelerate growth in this technology area. While not biomimetic, this proposal is clearly a biomimetic enabling idea.

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6. Nanotubes for Radiation Shielding

Hydrogen is known to be one of the best radiation shields. While carbon nanotubes have affinity for hydrogen, the problem is optimizing adsorption [1,2]. Adsorption optimization may be studied initially from the computational perspective. Information gleaned using this tool can then be translated into experimental efforts in the lab. Success in this endeavor can lead to the use of this material in applications like radiation shielding for spacesuits and space habitats required for planetary colonization in the future. Therefore, although this idea is not obviously biomimetic, it may be argued that radiation protection built into clothing mimics the way humans protect themselves from ultraviolet radiation by tanning as a result of the production of melanine pigments on the skin, in response to ultraviolet radiation exposure.

Skills exist in-house to begin the computational portion of this activity. Collaborations may be made with JSC and Rice Universities, who are experts in the fabrication of pure carbon nanotubes. Their participation would significantly enhance our activity in this area.

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7. Carbon Nanotube Surface Modification

Carbon nanotubes have great potential for enhancing properties of existing materials if it can be blended with these systems. However, while ways have been developed to permit the homogeneous dispersion of nanotubes in an organic matrix, there is much room left for developing new methods to create multiphase systems that include nanophase components like carbon nanotubes. One mode of accomplishing this is the modification of carbon nanotube surfaces by adding different functional groups. The functional groups can be chosen depending on the target use of the final multiphase system, so that effectively, the modified nanotube is custom designed for a specific use. The key is to enhance applications of nanotubes without deterioration of the properties that make them attractive in the first place. Because these materials will be new and are in the size domain that is about half to one order of magnitude larger than what we are used to working on, there is a need to develop new ways of characterizing the new materials. There is an extensive knowledge and skill base in-house on the characterization of fundamental properties at the atomic level. This knowledge base can be directed to the understanding of nanomaterials in order to fully exploit their potential for enhancing materials for aerospace applications. This activity is not biomimetic, but has potential for providing mechanisms for stimuli responsive materials that are biomimetic.

8. Surface Modification of Liquid Crystals

Like carbon nanotubes, desirable properties exhibited by liquid crystals can be used to enhanced the properties of existing systems. Again, the challenge here is finding ways to incorporate the liquid crystals into another matrix homogeneously. The interfacial properties of liquid crystals have been a subject of study for many years primarily because liquid crystal alignment is responsible for the interesting properties that liquid crystals possess [1,2]. This work should focus on compatibilizing liquid crystals with high performance materials used in aerospace applications. While not obviously biomimetic, this work can lead to the fabrication of biomimetic materials since the liquid crystals can provide a mechanism by which materials can respond to external stimuli.

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9. Peltier Effect for Conducting Polymers

Peltier effect is the temperature gradient produced by the flow of electricity through a circuit made of two dissimilar materials. The result is that one junction of the circuit cools down while the other junction gets hot. Conversely, when the circuit materials are subjected to temperature gradients, they can generate some power. These thermoelectric devices are typically made with semiconductor materials. There may be some weight savings advantage in developing conducting polymer devices that capitalize on the Peltier Effect to generate power. This device would be light, compact and have no moving parts. There is polymer development expertise in AMPB, although a conducting polymers is not an area of specialization. The knowledge and skill can be redirected to this effort however. In addition, some physics expertise present in NESB is necessary in this effort.

10. Metallized Foams

Polyimides are high performance materials known for their excellent thermooxidative and mechanical properties. They are typically used in film form or as matrices for tough composites. Polyimide foams have previously been studied as fire retardant materials as well. This material form offers the advantage excellent properties at a significant weight reduction because the properties are imparted by the polymer shell of "polyimide bubbles." A new application of this material as super-lightweight tank structures for cryogenic tank fuels is possible if these polymer microspheres are coated with a thin layer of metal through chemical vapor deposition (CVD). This would result in a structure similar to that of eggshells or peapods. The composite and metals expertise for this type of work already exist in AMPB and MTSB. Facilities are available to initiate this effort as well.

XIII. Conclusion

While the ideas for potential topics of research are by no means comprehensive, they demonstrate the diversity of problems for which biological systems may inspire solutions. There is no question that LaRC can make significant contributions in biomimetics. Implementation will require some paradigm shifts that are enumerated below:

1. Biomimetics must be viewed as a tool that can be used as a problem solving approach in a wide variety of aerospace related issues, rather than as a discipline.

2. As a problem solving approach, it should permeate existing programs. This implementation mode will require management unlike that of the traditional focused programs.

3. In order for biomimetics activities to be successful, it will require integrated multidisciplinary teams working in a coordinated fashion from the design to the systems engineering stage. This is contrary to the traditional, compartmentalized mode of design- and-integration-in-parts currently practiced.

These paradigm shifts can certainly be hurdled.

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13. ABSTRACT *(Maximum 200 words)*

This report represents an attempt to see if some of the techniques biological systems use to maximize their efficiency can be applied to the problems NASA faces in aeronautics and space exploration. It includes an internal survey of resources available at NASA Langley Research Center for biomimetics research efforts, an external survey of state of the art in biomimetics covering the Materials, Structures, Aerodynamics, Guidance and Controls areas. The Biomimetics Planning team also included ideas for potential research areas, as well as recommendations on how to implement this new program. This six-month survey was conducted in the second half of 1999.

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