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Adaptive Materials and Structures: A Workshop Report

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

Adaptive Materials and Structures

A Workshop Report

Committee for a Review of Adaptive Structural Materials Research That Could Pose a Threat to US National Security: A Workshop

Division on Engineering and Physical Sciences

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COMMITTEE FOR A REVIEW OF ADAPTIVE STRUCTURAL MATERIALS RESEARCH THAT COULD POSE A THREAT TO US NATIONAL SECURITY: A WORKSHOP

SHARON C. GLOTZER, *Chair*, University of Michigan
KENNETH I. BERNS, University of Florida College of Medicine
MIKHAIL SHAPIRO, University of California, Berkeley
GEORGE W. SUTTON, Consultant
ELIAS TOWE, Carnegie Mellon University
HADYN N. WADLEY, University of Virginia
STEVEN G. WAX, Strategic Analysis, Inc.

Staff

TERRY JAGGERS, Lead DEPS Board Director
DANIEL E.J. TALMAGE, JR., Study Director
SARAH CAPOTE, Research Associate
MARGUERITE SCHNEIDER, Administrative Coordinator
DIONNA ALI, Senior Program Assistant
CHRIS JONES, Financial Associate

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Preface

The workshop described in this report reflects the ongoing engagement between the National Research Council's (NRC's) Technology Insight—Gauge, Evaluate, and Review (TIGER) Standing Committee, the scientific and technical intelligence (S&TI) community, and the consumers of S&TI products.

I would like to express my appreciation to the members of the committee for their earnest contributions to the generation of this report. We are also grateful for the active participation of many members of the technology community as well as to the sponsor for its support. The committee would also like to express sincere appreciation for the support and assistance of the NRC staff, including Terry Jaggers, Daniel Talmage, Sarah Capote, and Dionna Ali.

Sharon Glotzer, *Chair*
Committee for a Review of Adaptive
Structural Materials Research That
Could Pose a Threat to US National
Security Interests: A Workshop

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Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Michael E. Kassner, Office of Naval Research,
Leslie Ann Momoda, HRL Laboratories, LLC,
Matthew V. Tirrell (NAE), University of Chicago, and
Edward White, Boeing Research and Technology.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the views of individual participants, nor did they see the final draft of the report before its release. The review of this report was overseen by Julia Phillips (NAE), Sandia National Laboratories. Appointed by the NRC, she was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Acronyms and Abbreviations

DARPA	Defense Advanced Research Projects Agency
DIA	Defense Intelligence Agency
IC	intelligence community
MAV	micro aerial vehicle
NRC	National Research Council
S&T	science and technology
S&TI	scientific and technical intelligence
SHM	structural health monitoring
TIGER	Technology Insight—Gauge, Evaluate, and Review
UAS	unmanned aerial system
UAV	unmanned aerial vehicle

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Introduction

INTRODUCTION AND STUDY ORIGIN

In 2012, the Defense Intelligence Agency (DIA) approached the National Research Council's TIGER standing committee and asked it to develop a list of workshop topics to explore the impact of emerging science and technology. One topic that came out of that list was adaptive structural materials. This workshop was held on July 11-12, 2012.

OBJECTIVES

The statement of task for the workshop can be found in Box 1-1. The objectives for the workshop were to explore the potential use of adaptive structural materials science and technology for military application. Understanding the current research in this area, and the potential opportunities to use this research by U.S. adversaries, allows the Defense Warning Office to advise U.S. policy makers in an appropriate and timely manner to take action on those areas deemed a national security risk. The workshop featured invited presentations and discussions that aimed to:

- Review the latest advances and applications both nationally and internationally related to adaptive structural materials scientific research and technology development.
- Review adaptive materials related to shape memory, magnetostrictive materials, magnetic shape memory alloys, phase change materials, and other metal and non-metallic materials research that may be uncovered during the course of workshop preparation and execution, to include all soft or nanoscale materials such as those used in human bone or tissue.
- Review modeling, processing and fabrication related to defining designs or design requirements for future military or dual-use air, space, land, sea or human systems.
- Review dual-use applications of commercial adaptive structural materials research and development, and the potential impacts on U.S. national security interests.

The workshop then focused on the application of adaptive structural materials technology and the national security implications for the United States, discussing U.S. and foreign researchers' current research, why the state or non-state actor application of a technology is important in the context of technological and military capabilities, and what critical breakthroughs are needed to advance the field.

WORKSHOP TOPICS

The Committee for a Review of Adaptive Structural Materials Research That Could Pose a Threat to US National Security Interests: A Workshop devised an agenda (see Appendix B) that helped the committee, sponsors, and attendees probe issues of national security related to materials as well as gain an understanding of potential vulnerabilities. This report summarizes the views expressed by individual workshop participants. While the committee is responsible for the overall quality and accuracy of the report as a record of what transpired at the workshop, the views contained in the report are not necessarily

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BOX 1-1

Statement of Task

An ad hoc committee will plan and conduct a two day workshop on selected national security implications of recent advances in adaptive structural materials. The workshop will feature invited presentations and panelists and include discussions on adaptive structural materials research and application that could create a technological surprise to our Nation's security and require US Defense Department intelligence monitoring and advance warning to allow national leaders to take action. The committee will plan the agenda, select and invite speakers and discussants, and moderate the discussions.

those of all workshop participants, the committee, or the National Research Council. This workshop was not intended to provide a comprehensive review of the state of adaptive structural materials.

REPORT STRUCTURE

The content of this report is divided between two chapters which correspond to the discussions and presentations on each day. Chapter 2 summarizes presentations and discussions held on the first day of the workshop, July 11, 2012. Chapter 3 chronicles the discussions from the second day of the workshop, July 12, 2012. The three appendices contain, in order, the biographies of the committee members, the agenda and list of attendees, and the biographies of the presenters. A distinction is noted in Chapters 2 and 3 as to whether the material is from the presenters or from participant discussion.

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First Day

ADAPTIVE SOFT AND BIOLOGICAL MATERIALS

Joerg Lahann, Professor, Chemical Engineering, Materials Science and Engineering, Bio Medical Engineering, University of Michigan.

Dr. Lahann introduced rationale for designing adaptive structural materials modeled on forms that exist in nature. For example, a number of insects and fish are able to dynamically change their exterior color to provide camouflage matching their environment. Such adaptive changes can arise from the activity of multiple distributed autonomous elements: fish melanophores (pigment cells) individually modify their morphology in response to environmental light cues such that their collective action lightens or darkens the animal's surface.

Similarly, synthetic materials exhibiting smart responses can be developed by engineering appropriate building blocks. For example, Dr. Lahann described work done in his laboratory to construct anisotropic microparticles that combine polymers with several different properties, such as color, magnetic susceptibility and deformation in response to temperature, solvents, electric fields, magnetic fields and pH. Such particles can individually take on a variety of shapes under different environmental conditions. When used together on a surface, such adaptive changes can alter the physical and chemical properties of that surface – for example its color or hydrophobicity. A key concept is the ability to design properties at the smallest element level that lead to useful responses in the bulk. Some bulk/surface properties would not be accessible without the use of this design approach.

Dr. Lahann noted that manufacturing anisotropic micromaterials is challenging, but advances made in microfluidics and chemistry by groups around the world have made it possible to do so consistently. The equipment necessary for such synthesis is not expensive. Forms of this concept have experienced broad adoption, for example in reading devices based on e-ink. Additional practical applications in development or under consideration include security inks, reconfigurable antennas, tunable filters and lenses, camouflage systems and medical diagnostics. While most technical demonstrations of adaptive materials based on anisotropic responsive microparticles have been in the liquid phase, he stated that it is also possible to structure solid materials and membranes with sufficient freedom of movement to take advantage of this approach. "However, I would not use these to paint a car," Dr. Lahann said.

Research groups whose work was cited by Dr. Lahann are based at academic institutions in the United States, Germany, Israel and Japan. Topics not covered in the presentation included self-healing materials and metamaterials.

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LEARNING FROM NATURE: BIOINSPIRED MATERIALS AND STRUCTURES

Vladimir Tsukruk, Professor, School of Materials Science and Engineering, Georgia Institute of Technology.

Dr. Tsukruk defined adaptive materials and structures as comprising the ability to sense external stimuli (ideally with low detection limit and large dynamic range) and actuate a calibrated reaction (e.g., change in organization) governed by a feedback loop to achieve a desired state (e.g. shape, compliance, appearance). He noted that many examples of adaptive and other uniquely beneficial materials and systems exist in nature, including:

- Adaptive colors in butterflies, octopi – photonic, sensing, camouflaging
- Dynamic adhesion in gecko feet – climbing, holding
- Self-healing biological parts – self-healing materials
- Reptilian locomotion – movement on complex terrains
- Dog canine – remote trace chemical sensing
- Silk materials – tough lightweight nanocomposites
- Night vision in some species – thermal sensors
- Wave tracking in seals and fish – underwater monitoring
- Spider hair air flow receptors – mechanical sensors

Devices with unique functionality and performance can be developed by characterizing the mechanisms underlying biological materials and recapitulating them synthetically. Using an example from his own laboratory, Dr. Tsukruk stated that the unique ability of snakes to detect small temperature changes as part of their infrared detection capabilities was traced to a special organ in which thermal expansion of air pockets leads to deformation of a membrane, which is detected in downstream cell signaling. Synthetic nanostructures with such a membrane arrangement were created and exhibited temperature sensitivity of 10 mK, with a spatial resolution of 30 μm when used in an array. Dr. Tsukruk said that at the time they were developed, these sensors showed unique performance compared to state-of-the-art bolometers. Importantly, these sensors are a passive material: temperature changes deform membranes so as to produce changes in reflectivity, which can be assayed as needed. He pointed out that a similar approach was used to mimic the ability of spiders to detect sound waves using unique hair structures, and to mimic the ability of fish to sense fluid velocity. In the latter case, a biomimetic structure had an unprecedented fluid motion detection limit of 2 μm/sec.

Dr. Tsukruk noted that the development of bio-inspired materials requires close multidisciplinary collaboration involving biologists and engineers. There are no comprehensive catalogs of useful mimicable biological materials/structures, and most are identified through word of mouth. Productive collaborations between engineers and biologists are rare and are usually initiated in the United States (sometimes with goal-driven introductions made by, e.g., DARPA). He stated that foreign biologists, who may not have previously thought about potential bioinspired applications, are drawn into collaborations with US engineers. In several cases they have subsequently established similar collaborations closer to home (examples were provided for Europe). A rough estimate is that fewer than 30% of engineers developing bioinspired materials have biomedical end-goals. Most are pursuing consumer product, defense or energy objectives.

While most of the work described by Dr. Tsukruk was carried out in the United States and Europe, he believed China would also make advances in this area. He provided the example of Peking University, which established a materials science program only ~5 years ago, but has managed to recruit a group of top scientists, most of whom previously held academic positions in the United States. Its graduate program was copied from Georgia Tech. In addition, Russia’s SkyTech and Saudi

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Arabia's KAUST (King Abdullah University of Science and Technology) may be supporting work in this area, according to Dr. Tsukruk.

ADAPTIVE GRANULAR MATTER

Heinrich Jaeger, William J. Friedman and Alicia Townsend Professor of Physics, University of Chicago.

Dr. Jaeger opened his presentation by remarking that granular materials exhibit far-from-equilibrium behavior. This behavior can be adaptive, and can yield a smart aggregate response from "dumb" ingredients. His work at the University of Chicago deals with granular[1] materials that can be used to form adaptive matter. These include pouring granular materials into a form, designing high strength, low-density structures, and making granular matter jam and unjam based on externally applied stress. This latter project was part of the completed JamBots program at DARPA. Research on granular matter can be traced back many years, but only recently has granular matter become of interest as an adaptive material.

Dr. Jaeger discussed both mesoscopic and macroscopic granular matter and then went on to discuss jamming. He mentioned that jamming is the emergent, cooperative process of a collection of objects getting stuck and becoming rigid. Jamming underlies some of the major scientific challenges in far-from-equilibrium physics, including understanding the glass transition. He noted that some researchers are working on optimizing the packing density of particles. Dr. Jaeger described how there has been rapid recent progress in simulating large collections of non-spherical particles, which has happened due to better computing hardware and algorithms.

Dr. Jaeger described soft robotics where jamming is the enabling technology. He showed different robots that can adapt to the surface of their structures, and also other structures that can adapt themselves to different surfaces (such as gripping a glass of water). An example is a robotic arm that can throw a dart onto a dartboard. These are passive, underactuated type universal grippers, being researched here in the United States.

In summary, Dr. Jaeger stated that granular materials are pervasive across all industries and technology with multitudes of applications. Granular matter is an amorphous collection of many (hard) particles, with interactions dominated by interfaces, and can be viewed as prototypical of far from-equilibrium behavior. Jamming is an important mechanism to produce reversible transformation between soft/rigid states in granular systems. He concluded by noting that with the proper design, granular materials can be adaptable, robust, and possibly "self-healing."

Q – What is around the corner? A – Jaeger responded with three topics: exploit particle shape, make ingredients "smart," and adaptive granular matter by design.

Q – Can you create materials that operate in a certain frequency range, and respond to sound waves? A – Yes, he said, research is being conducted to create materials that respond to certain frequency ranges. Sound waves are not yet being thoroughly researched (explorations are just preliminary).

ACTIVE AERO STRUCTURES

Daniel Inman, Department Chair, Aerospace Engineering and Clarence "Kelly" Johnson Professor, University of Michigan.

Dr. Inman presented to the workshop via video conferencing. He opened his presentation by outlining the areas that he would discuss. They included Morphing Aircraft, Solar Powered Aircraft, Structural Monitoring, Energy Harvesting, Origami Structures and Multifunctional Hybrids. Dr.

[1]Dr. Jaeger described granular matter as an amorphous collection of many (hard) particles in which emergent behavior arises from interaction at interfaces, and the internal particle properties are less important.

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Inman went on to explain their military significance, including quieter airplanes; improved performance; quiet, all-electric, long-range UAVs; self-powered sensor systems; and structural health monitoring systems. He discussed how birds have a unique ability to maneuver. This behavior has inspired developments in shape changing UAVs and MAVs that offer both stealth and agile maneuver advantages. He also described several different types of morphing structures from wings to engines that promise access to highly unusual flight envelopes. Next he explained how solar-powered use of structural health monitoring (SHM) methods to detect damage while structures are in service improves reliability and offers the possibility for other detections. He further explained that remote sensing, and place-and-forget sensing, require self-power, which implies the area of energy harvesting[2] of low power from solar, vibration and thermal gradients. This includes self-powered place-and-forget GPS monitoring systems. Dr. Inman also discussed harvesting mechanical vibration using the piezoelectric effect. The goals were to increase battery life, but it was found that only small amounts of useable electrical energy were produced. He then discussed concepts some ten to fifteen years out, including origami structures actuated by smart materials, autonomous behavior in structural and sensor systems, threat reduction systems that react to incoming threats by changing shape, and multifunctional, and functionally graded, hybrid composites. Dr. Inman concluded his presentation by summarizing that the active aero structures can provide stealth, remote sensing and functionality, improved vehicle performance, unique abilities to expand future capabilities and perhaps enable game changing solutions to security problems.

Q – Which other countries are doing similar research? A – He answered: China, Korea, Switzerland, Israel, and the United Kingdom.

35 YEARS OF ADAPTIVE STRUCTURES

Jay Kudva, Chief Executive Officer, NextGen Aeronautics.

Dr. Kudva opened his presentation by discussing flight from birds, to Icaraus, to the Wright brothers and on to jets. He went on to discuss how examples in biology inspire new projects to be developed. Dr. Kudva discussed a cuttlefish example which led to research areas in underwater vehicles and the use of different polymers. Some of the work was produced by looking at research from overseas and then building a very quiet underwater robot. He argued that an electroactive polymer capable of generating significant force is the holy grail for future research. An enabling vision for the future is a tailorable multifunctional material with stiffness on demand. Dr. Kudva showed another example of a morphing wing. One key point, he noted, was that the designers made several real models and tested them in wind tunnels to get key data. The researchers found that this was better than computational modeling. He pointed out that his company does not have large resources, but is focused, and can quickly catch up with competitors.[3] He mentioned that this is true for foreign countries as well. Some of the issues with flexible wings, he noted, were that the flexible skins break fairly quickly. Dr. Kudva mentioned that the ability to have adaptive controls as well as the ability to keep flying despite being damaged is very important. He believes that the United States is ahead in system level design and that smart structures are only 5 years out. He finished by discussing how the United States tends to have multiservice multifunction aircraft and how this can hurt the design of projects.

Q – Where do NextGen employees come from? A – With one degree of separation, all come from universities that Jay Kudva is familiar with (like UCLA). Occasionally, applicants are hired from oversees. However, the vast majority of its employees are from American universities (hired as they finish their engineering degrees).

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[2]Energy Harvesting as used here refers to capturing low levels of ambient waste energy to convert to useable electrical energy.

[3]For more information see http://www.nextgenaero.com/.

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Q – Competition oversees? A – He argued that American programs are certainly ahead. However, Kudva said, the Chinese are trying to break into NextGen's servers on a frequent basis, and there has been an explosion of patent applications from oversees.

ADAPTIVE STRUCTURES TECHNOLOGY FOR ADVANCED AIRCRAFT

Ed White, Adaptive Structures Technology Focus Team Leader, Associate Technical Fellow, Boeing Research and Technology.

Mr. White's talk on adaptive structures technology for advanced aircraft began by his discussing what is stopping adaptive airframes. He believes that solutions based on kinematics of rigid structures are usually too heavy and introduce concerns with added complexity, reliability, and maintainability. He then discussed the barriers that adaptive airframes have at the platform performance level. These include limited ability to do multidisciplinary analysis and optimization (MDAO) with adaptive airframe elements. Mr. White noted that researchers can create point designs for adaptive airframe solutions, but not within an MDAO environment, but he felt that this will need to change in the future.

Mr. White presented three key technology developments that are needed. These developments included compact, highly weight efficient variable geometry primary load paths; skins to provide fairings and gap closeouts to support the variable geometry; and highly integrated, multi-degree-of-semi freedom actuators. Next White discussed key implementation indicators. Some of these indicators included large-scale testing of any of the technology needs area previously mentioned, and testing beyond a technology readiness level of 6.

To summarize, White suggested that adaptive structures (applied to large structures) require technology development in the three key technology development areas. He also believes that design of adaptive airframes must be performed as part of a system level trade off and that the development of these tools lag significantly behind the current research on adaptive structural materials.

MAGNETIC SHAPE MEMORY

Manfred Wuttig, Professor, and Director of Graduate Program, Department of Materials Science and Engineering, University of Maryland.

Professor Wuttig noted that shape memory alloys are a general class of materials that remember their original shape. They are potentially useful in actuators that may be designed to change shape, stiffness, position, natural frequency of vibration, and other mechanical characteristics in response to temperature or electromagnetic fields. He stated that magnetic shape memory alloys are ferromagnetic materials that exhibit tensile strain (with a measurable relative physical extension that can be as large as 10%) when a magnetic field is imposed on the material. The physical extension depends on the magnetic anisotropy of the material, where the magnetic domains line up much more readily in one direction than in the other. The main advantage of magnetic shape memory alloys over conventional shape memory alloys, he argued, is that the former can respond faster to changes than the latter. Magnetic field effects operate on a faster time scale than thermal effects.

Dr. Wuttig noted that the leading foreign research work in magnetic shape memory alloys is being carried out primarily in Europe (University of Helsinki, University of Dresden, and University of Barcelona), Russia (Kiev University), and Asia (Tohoku University and Tsing-Hua University). In the United States, he said, this kind of work is being carried out at Caltech, MIT, and the University of Maryland.

Dr. Wuttig stated that most of the work in this area is still in its infancy. The synthesis of ferromagnetic materials for dynamic adaptive applications is still a challenge. The unit volumetric change for applied input energy remains too high. Use of magnetic shape memory alloys in large

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adaptive structures in the aerospace industry, for example, is nonexistent. However, he noted, hobby applications in model toy aircraft where the flight surfaces are controlled by magnetic shape memory alloys are probably feasible.

MULTIFUNCTION FOR PERFORMANCE TAILORED STRUCTURES

Leslie Momoda, Director, Sensors and Materials Laboratory, HRL Laboratories.

Dr. Momoda began with a discussion of multifunctional structurally adaptive materials, including those that have controllable electrical, thermal, and acoustic transmission or that exhibit color or surface texture adaption. A potential approach is to embed the responsive materials in a structural matrix (one that supports mechanical stresses well) such as a composite, foam or microlattice material. The system benefits from such an advance, she noted, would be significant, including lighter, longer-range vehicles, more payload capacity, mission adaptive behavior (including camouflage), and self-diagnosis, healing and targeted maintenance. Her presentation reviewed developments in macro-scalable integrated thermal management, self-healing structures based on micro-vascular concepts, meta materials for acoustic and EMI shielding, soft materials including shape memory polymers and variable stiffness composites. Dr. Momoda discussed multifunctional battery work including batteries that can be painted on a surface (Rice University), carbon fiber batteries (KTH, Sweden), fiber reinforced lithium ion batteries (HRL) and a BAE fiber-based Ni-MH chemistry system. She reviewed the many challenges that will be encountered in realizing these concepts and discussed potential applications in small unmanned systems and robotics. She stated that tracking developments in these areas is likely to provide early warning of potentially game-changing advances by adversaries. Her presentation also included a comprehensive bibliography of relevant research papers and reports.

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Second Day

Several participants argued that UAVs (UASs) in general are of high importance, but the least likely to benefit from adaptive materials and structures. They are inexpensive and easy to build, and currently, very difficult to defend against, even without reconfigurability or adaptive structural components. It was pointed out that today's UAVs already benefit from adaptive materials such as shape memory alloys and electroactive polymers. Participants discussed whether marginal incremental performance enhancements are expected by the use of additional adaptive materials.

Participants then followed several lines of discussion dealing with vulnerabilities including: morphing, adaptive marine vehicles, adaptive optics, and granular materials. At the end of the session, the chair of the committee asked for some final thoughts from the attendees.

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Appendixes

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Appendix A
Committee Biographies

Sharon C. Glotzer (*Chair*) is the Stuart W. Churchill Collegiate Professor of Chemical Engineering and professor of materials science and engineering, at the University of Michigan, Ann Arbor, and director of research computing in the UM College of Engineering. She also holds faculty appointments in physics, applied physics, and macromolecular science and engineering. She received a B.S. in physics from UCLA and a Ph.D. in physics from Boston University. Prior to Michigan, she worked at the National Institute of Standards and Technology. Her research focuses on computational nanoscience and simulation of soft matter, self-assembly and materials design, and computational science and engineering, and is sponsored by the DoD, DoE, NSF, and the J.S. McDonnell Foundation. Dr. Glotzer is a fellow of the American Physical Society, a National Security Science and Engineering Faculty Fellow, and was elected to the American Academy of Arts and Sciences in 2011. She has served on the National Research Council's Solid State Sciences Committee; Technology Warning and Surprise study committee; Biomolecular Materials and Processes study committee; Modeling, Simulation, and Games study committee; and on the Technology Insight: Gauge, Evaluate, and Review (TIGER) Committee. She is involved in roadmapping activities for computational science and engineering, including chairing or co-chairing several workshops, steering committees, and pan-agency initiatives, and serves on the advisory committees for the DOE Office of Advanced Scientific Computing and NSF Directorate for Mathematical and Physical Sciences. Glotzer is also co-founding director of the Virtual School for Computational Science and Engineering (VSCSE) under the auspices of the NSF-funded Blue Waters Petascale Computing Project at the National Center for Supercomputing Applications (NCSA).

Kenneth I. Berns (NAS/IOM) is director and distinguished professor, UF Genetics Institute/Molecular Genetics and Microbiology, Medicine, University of Florida. He has served as a member of the Composite Committee of the United States Medical Licensing Examination, chairman of the Association of American Medical Colleges, president of the Association of Medical School Microbiology and Immunology Chairs, president of the American Society for Virology, president of the American Society for Microbiology, and vice-president of the International Union of Microbiological Societies. He is a member of the National Academy of Sciences and the Institute of Medicine. Dr. Berns's research examines the molecular basis of replication of the human parvovirus, adeno-associated virus, and the ability of an adeno-associated virus to establish latent infections and be reactivated. His work has helped provide the basis for use of this virus as a vector for gene therapy. Dr. Berns's M.D. and his Ph.D. in biochemistry are from the Johns Hopkins University.

Mikhail Shapiro is a neuroscientist, engineer, and technology entrepreneur focused on developing better ways to study the brain's activity and treat neurological and psychiatric disease. Dr. Shapiro has been named as a Miller Research Fellow at the University of California at Berkeley to develop an independent research program focused on ways to non-invasively sense

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and manipulate brain activity at the molecular level. He studied neuroscience at Brown and received his Ph.D. in biological engineering from MIT as a Hertz and Soros Fellow. Working with Alan Jasanoff and Robert Langer, Shapiro created the first-ever functional MRI sensors for neurotransmitters. He was also a cofounder of Cyberkinetics Neurotechnology Systems, whose BrainGate technology allowed paralyzed people to control external devices directly with their thoughts. As a venture principal at Third Rock Ventures, an $800 million life sciences venture capital firm, Shapiro helped launch companies focused on novel treatments for chronic pain, cancer, and other diseases. In 2010 he was recognized by the Technology Review as one of the world's top 35 innovators under age 35.

George W. Sutton (NAE) is a consultant. He received his B.M.E (with honors) in mechanical engineering from Cornell University and his Ph.D. in mechanics and physics (magna cum laude) from Caltech. He made the first measurements of the stresses in a solid caused by cavitation. He also was the first to measure the heat transfer rate in the throat of a rocket nozzle at Caltech's Jet Propulsion Laboratory. At G.E., he invented the first successful heat protection material for hypersonic reentry into the Earth's atmosphere. It was an active material – as it was heated during reentry the gases driven off it reduced the heat transfer to the surface. It, and its variants, have been used on all reentry vehicles and satellite film recovery vehicles, including today's. At the Avco-Everett Research Laboratory he helped develop high-power lasers. For its commercial electron-beam ionized, electrically pumped closed cycle carbon dioxide laser, his contribution was the heat-conducting foil for the electron beam. He also developed the prototype of the electrical transcutaneous energy transfer device, using ferrites, for artificial hearts that has FDA approval for 5,000 transplants. His work on ballistic missile defense included cooled windows, uncooled optical dome and window thermal radiance, stresses, and optical distortions. This included analysis of deformable mirrors to correct aero-optical distortions. He also analyzed the boresight distortion of optical seekers on interceptors due to bending of the vehicle airframe when the divert motors fire. He has written over 100 papers and coauthored three books. He is a member of the National Academy of Engineering and has served on six studies. He was editor-in-chief of the *AIAA Journal* for almost 30 years, which he performed in addition to working full time. He is an Honorary Fellow of the AIAA and has received medals and awards for his work.

Elias Towe is currently a professor of electrical and computer engineering, and the Albert and Ethel Grobstein Professor of Materials Science and Engineering at Carnegie Mellon University. He was educated at the Massachusetts Institute of Technology (MIT), where he received the bachelor of science, master of science, and the Ph.D. degrees from the Department of Electrical Engineering and Computer Science. Dr. Towe was a Vinton Hayes Fellow at MIT. After leaving MIT he became a professor of electrical and computer engineering, and engineering physics at the University of Virginia. He also served as a program manager in the Microsystems Technology Office at the Defense Advanced Research Projects Agency (DARPA) while he was a professor at the University of Virginia. In 2001, he joined the faculty at Carnegie Mellon University. Towe is a recipient of several awards and honors that include the National Science Foundation Young Investigator Award, the Young Faculty Teaching Award, and the Outstanding Achievement from the Office of the Secretary of Defense. He is a fellow of the Institute of Electrical and Electronics Engineers (IEEE), the Optical Society of America (OSA), the American Physical Society (APS), and the American Association for the Advancement of Science (AAAS).

Haydn N. Wadley is a university professor and Edgar Starke Professor of Materials Science and Engineering at the University of Virginia. He joined the department of materials science and engineering in October 1988. He has very broad interests in materials science. His current research explores high-temperature thermal protection systems (thermal barrier coatings, liquid metal heat plates for hypersonic vehicle leading edges) and new materials for the mitigation of

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high-intensity dynamic loads. He has addressed many fundamental questions associated with the atomic assembly of nanoscopic materials from the vapor phase, the topological structuring of cellular materials, and the processing of high-performance composites. These fundamental studies have been used to develop models and numerical simulations that expose the linkages between a material's composition/synthesis and its performance. Some of these models have been coupled with in-situ (ultrasonic and electromagnetic) sensors and nonlinear, feedback control algorithms to implement intelligent process control concepts. He has invented and commercialized several vapor deposition technologies that enable the growth of novel thin films and coatings, and developed numerous multifunctional cellular materials including those that support stress while also serving as impact energy absorbers, heat exchange media, electro-chemical power storage systems, or shape morphing structures. Dr. Wadley has spent many years helping the Department of Defense to identify new technology development opportunities in areas as diverse as the exploitation of space and humanitarian relief operations. Haydn Wadley received his bachelor's degree in chemical physics and his PhD in physics from the University of Reading (UK). Prior to joining the University of Virginia in 1988 he was a senior scientist at the National Institute of Standards and Technology and a leader of its advanced sensors group. He began his research career at the Atomic Energy Research Establishment (Harwell), where he worked on the origins of acoustic emission in materials and radiation damage mechanisms in refractory metals. He has published 411 papers, co-authored a book on cellular materials, holds 18 U.S. patents, and is a fellow of the American Society for Materials and the recipient of several awards.

Steven G. Wax is chief technical officer and executive vice president at Strategic Analysis, Inc. He is supporting defense clients in strategic planning and technology innovation across a range of scientific and engineering disciplines including the physical sciences, materials, biology, biomedical sciences, neuroscience, social sciences, and mathematics. Prior to executive level positions at Strategic Analysis, Inc. and SRI International, Dr. Wax spent 35 years working for the Department of Defense as a civilian and a military officer. During that period, he performed and managed government R&D across a broad spectrum of classified and unclassified technology areas. His last government position was as director of the Defense Science Office, Defense Advanced Research Projects Agency (DARPA), a $400 million per year office whose technology purview included physical sciences, materials, mathematics, human effectiveness, and the biological sciences, including biological warfare defense. As director, Dr. Wax was responsible for the office's investment strategy as well as the transition of office technologies to the military. Previous government positions also include deputy director of the Technology Reinvestment Project and an assignment to the National Reconnaissance Office. Dr. Wax is currently a member of the National Materials Manufacturing Board, the Defense Sciences Research Council's Red Team, and past member of Sandia National Laboratory's External Review Panel for Materials. He recently served as an external reviewer of ONR's Discovery and Innovation portfolio. He is also a member of the AFRL's Human Effectiveness Directorate's independent Review Team and is serving on the FY12 Committee of Visitors for NSF's Division of Civil, Mechanical, and Manufacturing Innovation. In 2009, he was the winner of the George Kimball Burgess Memorial Award. Notable technical accomplishments include a major role in the development of DARPA's strategic plans for both biology and material science as well as the development of two material science program thrusts (Intelligent Processing of Materials and Accelerated Insertion of Materials) that have revolutionized materials processing and insertion. His publications include a review paper on electroactive polymers and one on smart materials. Dr. Wax has a PhD in ceramic engineering from Georgia Institute of Technology, an MS in chemical engineering from the University of Illinois, and a BS in chemical engineering from the University of Massachusetts. Dr. Wax is a retired Air Force Officer.

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Appendix B
Workshop Agenda and Participants

AGENDA

Workshop on Adaptive Structural Materials
July 11-12, 2012
Washington, D.C.

Adaptive Soft and Biological Materials
Joerg Lahann, Professor
University of Michigan

Learning from Nature: Bioinspired Materials and Structures
Vladimir Tsukruk, Professor
Georgia Tech

Adaptive Granular Matter
Heinrich Jaeger, William J. Friedman and Alicia Townsend Professor of Physics
University Chicago

Active Aero Structures
Daniel Inman, Department Chair and Clarence "Kelly" Johnson Professor
University of Michigan

Jay Kudva, CEO
NextGen

Adaptive Structures Technology for Advanced Aircraft
Ed White, Structures Research Engineer
Adaptive Materials and Structures
Boeing

Magnetic Shape Memory
Manfred Wuttig, Graduate Program Director
Department of Materials Science and Engineering
University of Maryland

Multifunction for Performance Tailored Structures
Leslie Momoda, Director
Sensors and Materials Laboratory
HRL Laboratories

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PARTICIPANTS

Committee

Kenneth Berns, University of Florida
Sharon Glotzer, University of Michigan
Mikhail Shapiro, University of California, Berkeley
George Sutton, consultant
Elias Towe, Carnegie Mellon University
Haydn Wadley, University of Virginia
Steven Wax, Strategic Analysis, Inc.

Speakers

Daniel Inman, University of Michigan (via VTC)
Heinrich Jaeger, University of Chicago
Jay Kudva, NextGen Aeronautics, Inc.
Joerg Lahann, University of Michigan (via VTC)
Leslie Momoda, HRL Laboratories, LLC.
Vladimir Tsukruk, Georgia Institute of Technology
Edward White, Boeing Research and Technology
Manfred Wuttig, University of Maryland

Staff

Dennis Chamot, Associate Executive Director, Special Projects
Terry Jaggers, Board Director
Daniel Talmage, Study Director
Sarah Capote, Research Associate
Dionna Ali, Senior Project Assistant

Agency Represented

Defense Intelligence Agency
Department of Defense
National Air and Space Intelligence Center

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Appendix C
Speaker Biographies

Daniel J. Inman, Ph.D.,
Chair, Department of Aerospace Engineering, University of Michigan

Dr. Inman received his Ph.D. from Michigan State University in mechanical engineering in 1980 and spent 14 years at the University of Buffalo, followed by 19 years at Virginia Tech. Since 1980, he has published eight books (on vibration control, statics, dynamics, and energy harvesting), eight software manuals, 20 book chapters, 300 journal papers, and 555 proceedings papers, given 56 keynote or plenary lectures, graduated 56 Ph.D. students, and supervised more than 75 MS degrees. He is a fellow of the American Academy of Mechanics (AAM), the American Society of Mechanical Engineers (ASME), the International Institute of Acoustics and Vibration (IIAV), and the American Institute of Aeronautics and Astronautics (AIAA). He is currently technical editor of the *Journal of Intelligent Material Systems and Structures* (1999-). He was awarded the ASME Adaptive Structures Award in April 2000, the ASME/AIAA SDM Best Paper Award in April 2001, the SPIE Smart Structures and Materials Life Time Achievement Award in March 2003, the ASME/Boeing Best Paper Award by the ASME Aerospace Structures and Materials Technical Committee 2007, the ASME Den Hartog Award in 2007, and the Lifetime Achievement Award in Structural Health Monitoring in 2009. He has served as a member-at-large on the Society of Experimental Mechanics Executive Board (2008-2010) and as a former chair of the ASME Applied Mechanics Division.

Heinrich Jaeger, Ph.D.,
William J. Friedman and Alicia Townsend Professor of Physics, University of Chicago

Dr. Jaeger received his Ph.D. in physics in 1987, working under Allen Goldman at the University of Minnesota on ultrathin superconducting films. After a postdoctoral position at the University of Chicago, he moved to the Netherlands in 1989 to take up a position as senior researcher at the Delft Institute for Microelectronics and Submicrontechnology. He joined the faculty at the University of Chicago in 1991, directing the Chicago Materials Research Center from 2001 to 2006, and the James Franck Institute from 2007 to 2010. Jaeger is the recipient of a David and Lucille Packard Fellowship for Science and Engineering, an Alfred P. Sloan Fellowship, and a Research Corporation Cottrell Scholarship. He received the University of Minnesota Outstanding Achievement Award and a Llewellyn John and Harriet Manchester Quantrell Award for Excellence in Undergraduate Teaching. Jaeger's research interests focus on the understanding and control of materials, crossing the boundaries between "hard" condensed matter physics (electronic and magnetic properties of metals and superconductors) and "soft" condensed matter physics (granular materials, colloids, nonlinear dynamics). Currently, his group is involved in projects ranging from the assembly of next-generation nanostructures to investigations of the complex nonlinear behavior of granular materials (these materials include grain, gravel, or

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pharmaceutical pills all the way to ultrafine powders). Granular materials are key to many industrial processes and also provide new enabling technology for soft robotics.

Jay N. Kudva, Ph.D.,
President/CEO, NextGen Aeronautics, Inc.

Dr. Kudva received his BS in aeronautical engineering from the Indian Institute of Technology Madras in 1973, and his MS and PhD degrees in aerospace engineering from Virginia Tech in 1976 and 1979, respectively. He was a faculty member at RPI from 1979 to 1980. He worked at Northrop Grumman Corporation from 1980 to 2002, where he managed a structures R&D group and spear-headed division activities on smart materials and adaptive aircraft. During this time, he also taught graduate and undergraduate courses at UCLA, USC, CSULB, CSULA, and Loyola Marymount Universities. In 2003, he founded NextGen Aeronautics with the explicit purpose of developing revolutionary technologies and designs for the next century of flight. NextGen has seen rapid growth since its inception and currently has 36 employees and has completed or has on-going over 100 contracts from DARPA, NASA, AFRL, NAVAIR, and the U.S. Army as well as major defense contractors. As a prime example of NextGen's innovation, under DARPA sponsorship, NextGen designed, developed, and flight-tested the world's first two and only in-flight morphing wing autonomous UAVs. This was done in head-to-head competition with major aerospace system integrators. NextGen has a proven record of successfully teaming with universities, small companies, and major defense contractors. Dr. Kudva has published over 60 papers and reports and holds two joint patents on conformal load bearing antenna structures (CLAS). He has delivered invited and keynote talks at universities, national and international conferences and government laboratories. He was honored with the SPIE Smart Structures and Materials Lifetime Achievement Award in 2007 and the AIAA ASME Adaptive Structures Prize in 2010. He is an associate fellow of AIAA.

Joerg Lahann, Ph.D.,
Professor, Departments of Chemical Engineering, Materials Science and Engineering,
Professor, Biomedical Engineering, and Macromolecular Science and Engineering

Dr. Lahann received his B.S. in chemistry from the University of Saarland and an M.S. in chemistry and a Ph.D. macromolecular chemistry from RWTH Aachen University in 1998. He was a postdoctoral associate at MIT's Department of Chemical Engineering from 1999 to 2001. After his postdoctoral postion at Harvard-MIT Division of Health Sciences and Technology from 2002 to 2003 he joined the University of Michigan faculty as an assistant (2003-2008) and then associate (2008-2012) professor. As of 2012 he became a professor and the director of Biointerfaces Institute. He has been the co-director of the Institute of Functional Interfaces at the Karlsruhe Institute of Technology in Germany since 2009. His research interests include designer surfaces, advanced polymers, biomimetic materials, microfluidic devices, engineered microenvironments, and nano-scale self-assembly. Dr. Lahann has won several awards, including the DOD IDEA Award in 2006 and the NSF CAREER Award and Technology Review TR100 Young Innovator Award in 2004.

Leslie Ann Momoda, Ph.D.,
Director, Sensors & Materials Laboratory, HRL Laboratories, LLC, Malibu, Calif.

Dr. Momoda joined HRL Laboratories in 1990 after receiving a B.S. in chemical engineering and M.S. and Ph.D. degrees in materials science and engineering at UCLA. At HRL, she has performed research and development projects dealing with mixed metal oxide materials for electronic, optical, and chemical sensor applications as well as novel smart materials. She has

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over 20 years of experience in the fields of materials synthesis, processing, and characterization for electronic and structural applications. As a research department manager for 10 years, Dr. Momoda led several major projects in smart materials, materials and chemistry for thermal management, gas sensing, and the modeling and prediction of materials reliability. She was also project manager of the DARPA Compact Hybrid Actuator Program (CHAP). As a laboratory director, she now manages a laboratory of 70 scientists and engineers with research in the areas of novel, lightweight, architected materials, active and adaptive structures, electrochemical analysis, energy storage and generation devices, scalable nano-materials processing, novel detector materials, and high Q MEMs devices. She is a member of the Materials Research Society and is on the advisory board for the Materials Science and Engineering departments at the University of California, Los Angeles, the University of California, Riverside, and the University of Southern California.

Vladimir V. Tsukruk, Ph.D.,
Professor, School of Materials Science and Engineering,
Georgia Institute of Technology
Co-Director, Air Force BIONIC Center of Excellence

Vladimir V. Tsukruk received his MS degree in physics from the National University of Ukraine, and his PhD and DSc in chemistry and polymer science from the National Academy of Sciences of Ukraine. He carried out his postdoctoral research at the universities of Marburg, Germany, and Akron, United States. He is currently a professor at the School of Materials Science and Engineering, Georgia Institute of Technology and a co-director of the Air Force BIONIC Center of Excellence. He was elected an APS Fellow in 2010 and an MRS Fellow in 2011. He serves on the editorial advisory boards of six professional journals, has co-authored around 330 refereed articles in archival journals, as well as five co-edited or co-authored books and has organized 10 professional conferences. He is a co-founder of the company SEMADyne. His research in the fields of surfaces and interfaces, molecular assembly, and nano- and bioinspired materials has recently been recognized by the Humboldt Research Award (2009) and the NSF Special Creativity Award (2006), among others, and is supported by NSF, AFOSR, ARO, DARPA, DOE, and private industry. Tsukruk has vast expertise in the fabrication of interfacial nanostructures with emphasis on responsive nanomaterials and biosensing structures and their comprehensive characterization. He has established an excellent experimental facility at a Microanalysis Center with a range of microscopic and spectroscopic methods. His book *Scanning Probe Microscopy of Soft Matter: Fundamentals and Practices* (Wiley, 2012) is a comprehensive textbook on SPM applications of synthetic and biological materials. Overall, he has trained about 50 students and postdoctoral associates who currently work in academia and in leading research centers (MIT, Washington University, AFRL, Dow, DuPont, and Intel).

Edward V. White
Boeing Associate Technical Fellow, Enterprise-wide Adaptive Structures Technology Focus Team Leader, Lead for Structural Health Management, St. Louis, Missouri

Mr. White has 36 years of experience at the Boeing Company in the areas of structural dynamics and loads, and for the last 22 years in smart structures technology development. Since June 1994 he has been team leader of the Smart Structures and Systems team in the Boeing Research and Technology organization in St. Louis. As team leader, Mr. White is responsible for leading a multi-disciplinary/multi-site group pursuing both contracted and internal research and development into adaptive structures technology. The Smart Structures and Systems team is developing technologies such as embedded sensors and actuators and for both shape change and

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load suppression applications, technology and methods for embedding devices into composite materials, information processing of data collected from these systems, control of smart structures and applications of intelligent systems technology such as neural networks and expert systems. The primary application thrust areas of this research are adaptive structures, including shape change, morphing, and load and vibration/acoustics suppression; structural health management; and applications of intelligent systems technology to structures control and data processing. Mr. White is currently principal investigator (PI) for a NASA contract to develop novel control effectors for generation-after-next commercial aircraft. The research is based on the variable geometry raked wing tip concept developed by Mr. White and others. He is also PI for the NextGen Aeronautics lead contract on the DARPA/STO Structural Logic program. He also is the PI for two Boeing internally funded research projects in adaptive structures. Mr. White was previously the program manager for the Smart Aircraft and Marine Projects Demonstration (SAMPSON) program. Under a cooperative agreement with DARPA, the SAMPSON program demonstrated high-pay-off applications of smart structures technology to aircraft inlets and marine turbomachinery. The SAMPSON program was conducted by a formal consortium of three major organizations, then McDonnell Douglas Aerospace, General Dynamics Electric Boat, and Pennsylvania State University. Mr. White held the overall lead position for the SAMPSON consortium with direct responsibility to the DARPA customer. Mr. White also managed the U.S. Air Force Active Buffet Load Alleviation program. The focus of this program is to study the design and integration of an active buffet load alleviation system for fighter aircraft. Mr. White received his B.S. in aerospace engineering from Pennsylvania State University in 1976 and an M.S in mechanical engineering from Washington University in 1984.

Manfred Wuttig, Ph.D.,
Professor, and Director of Graduate Program, Materials Science and Engineering, University of Maryland

After having finished his physics and physical metallurgy education in Dresden and Berlin in 1960 Manfred Wuttig moved to the University of Illinois at Urbana-Champaign in January 1962 as a postdoctoral associate. At this time, spurred by nuclear reactor safety concerns, defects in solids constituted a major portion of materials science, and his first publications addressed this theme. Related work on magnetic properties of defects earned him an invitation to Grenoble, where he worked in the laboratory at Institute Neel. Teaching in a metallurgy department (University of Missouri, Rolla, 1965-1984), he became interested in martensite. He moved to the University of Maryland via a stint as program director at NSF, and started work on ferroic films which later on broadened to multiferroics. This lead to a MURI, which triggered the worldwide explosion of this topic. Today, Dr. Wuttig's interests are turning from hard to soft multiferroics. Here, the intriguing possibility exists that one can control ferroic properties with light. He is an internationally recognized materials scientist with 256 publications in high impact journals and 7,900 citations.

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