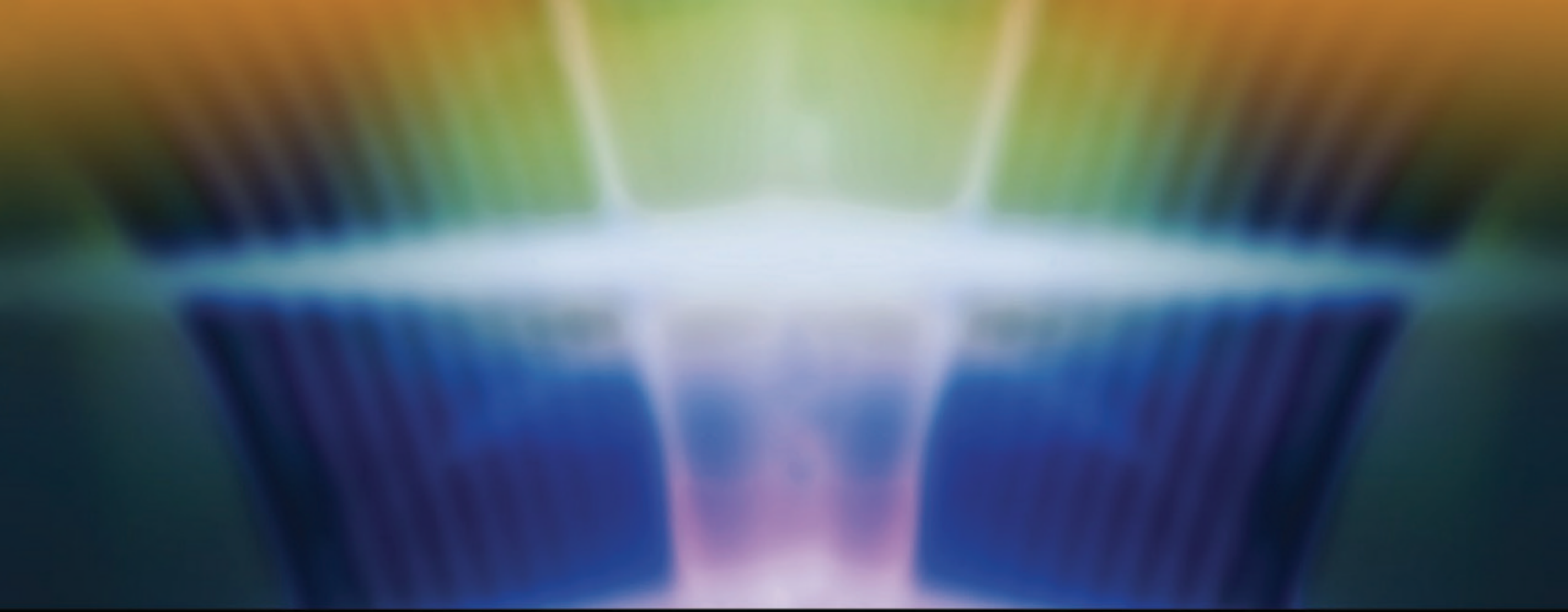
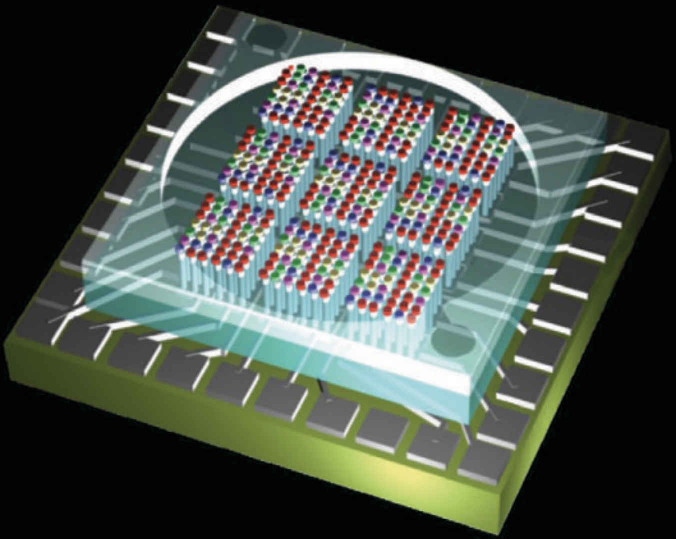


Nanotechnology in Space Exploration

Report of the National Nanotechnology Initiative Workshop
August 24–26, 2004



About the Nanoscale Science, Engineering, and Technology Subcommittee

The Nanoscale Science, Engineering, and Technology (NSET) Subcommittee is the interagency body responsible for coordinating, planning, implementing, and reviewing the National Nanotechnology Initiative (NNI). NSET is a subcommittee of the National Science and Technology Council (NSTC), which is one of the principal means by which the President coordinates science, space, and technology policies across the Federal Government. The National Nanotechnology Coordination Office (NNCO) provides technical and administrative support to the NSET Subcommittee and supports the subcommittee in the preparation of multiagency planning, budget, and assessment documents, including this report.

For more information on NSET, see http://www.nano.gov/html/about/nsetmembers.html.

For more information on NSTC, see http://www.ostp.gov/nstc/.

For more information on the NNI, NSET, and NNCO, see http://www.nano.gov.

About this document

This document is the report of a workshop held under NSET auspices in August 2004 seeking input from the research community on the NNI research agenda relating to space exploration. It was used as input for the NNI Strategic Plan released in December 2004. The meeting was jointly sponsored by the National Aeronautics and Space Administration, and, through the NNCO, the other member agencies of the NSET Subcommittee.

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Nanotechnology in Space Exploration

Report of the National Nanotechnology Initiative Workshop
August 24–26, 2004, Palo Alto, CA

Workshop Co-Chairs

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Sponsored by

National Science and Technology Council
Committee on Technology
Subcommittee on Nanoscale Science, Engineering, and Technology

National Aeronautics and Space Administration

ACKNOWLEDGMENTS

The sponsors of this report wish to extend gratitude and appreciation to all the participants in and contributors to the August 24–26, 2004 workshop held in Palo Alto, California (see Appendix B), and particularly to the workshop co-chairs, Meyya Meyyappan of NASA Ames Research Center and Minoo Dastoor of NASA Headquarters. Special thanks are due to the principal authors of this report, who are listed at the beginning of each chapter, and to the other members of the workshop organizing committee:

James Arnold, University of California, Santa Cruz
Pedro J. Medelius, Kennedy Space Center
Mike Postek, National Institute of Standards and Technology
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Jeff Schloss, National Institutes of Health
Mia Siochi, NASA Langley Research Center
Sharon Smith, Lockheed Martin
Benny Toomarian, Jet Propulsion Laboratory
Leonard Yowell, NASA Johnson Research Center
Mary Zeller, NASA Glenn Research Center

The presentations and discussions at that workshop provided the foundation for this report.

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The workshop was sponsored by the National Aeronautics and Space Administration (NASA) and, through the National Nanotechnology Coordination Office (NNCO), the other member agencies of the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee, Committee on Technology, National Science and Technology Council. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the United States Government or the authors' parent institutions.

PREFACE

This report on nanotechnology in space exploration is one of a series of reports resulting from topical workshops convened during 2003 and 2004 by the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the National Science and Technology Council's Committee on Technology through the National Nanotechnology Coordination Office (NNCO). The workshops were part of the NSET Subcommittee's long-range planning effort for the National Nanotechnology Initiative (NNI), the multiagency Federal nanotechnology program. The NNI is driven by long-term goals based on broad community input, in part received through these workshops. The NNI seeks to accelerate the research, development, and deployment of nanotechnology to address national needs, enhance our nation's economy, and improve the quality of life in the United States and around the world, through coordination of activities and programs across the Federal Government.

At each of the topical workshops, nanotechnology experts from industry, academia, and government were asked to develop broad, long-term (ten years or longer), visionary goals and to identify scientific and technological barriers that, once overcome, will enable advances toward those goals. The reports resulting from this series of workshops inform the respective professional communities as well as various organizations that have responsibilities for coordinating, implementing, and guiding the NNI. The reports also provide direction to researchers and program managers in specific areas of nanotechnology R&D regarding long-term goals and hard problems.

This workshop was convened to gain input from stakeholders in the field of nanotechnology on the enabling capabilities and products that could impact robotic and human exploration of space. Six broad areas were identified as critical to meet space mission needs: nanomaterials, nanosensors and instrumentation, microcraft, micro/nano-robotics, nano-micro-macro integration, and astronaut health management. The objectives of the workshop were to articulate a vision for each of the above areas, review the state of the art, define the major challenges, and develop near- and long-term goals.

The findings from this workshop were taken into consideration in preparation of the updated NNI Strategic Plan released in December 2004 and were used as input to the development of programs that make up portions of the fiscal year 2006 and 2007 NNI budgets requested for the National Aeronautics and Space Administration and other NNI participating agencies.

On behalf of the NSET Subcommittee, we wish to thank Meyya Meyyappan and Minoo Dastoor for their creativity and hard work in conducting an outstanding workshop and in preparing this report. We also thank all the speakers, session chairs, and participants for their time and efforts to make the workshop a success and to draft this report. Their generous sharing of research results and insights ensures that this document will serve as a reference for the NNI.

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Nanoscale Science,
Engineering, and Technology
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Director
National Nanotechnology
Coordination Office

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EXECUTIVE SUMMARY

INTRODUCTION

Ever since man started taking control of the environment and shaping things to meet human needs, he has endeavored to understand matter at its fundamental level. Since the dawn of the 21st century it has become possible to study, design, and synthesize structures with the precision of one-billionth of a meter (nanometer). Nanoscience is the study of the fundamental principles of matter at the scale of ~1–100 nm, while nanotechnology is the application of such knowledge to making materials and devices.

Nanostructures are among the smallest entities that can be made, but more importantly, nanostructures possess unique features. At the nanometer scale (“nanoscale”), many properties of matter are different from the properties at the macroscale. As an example, gold nanoparticles possess entirely different chemical, physical, electrical, magnetic, and collective properties than bulk gold. The understanding and control of such unique properties enable nanofabrication. Fundamental research at the nanoscale is crucial in order to understand how matter is constructed and how its properties reflect its components, such as atomic composition, shape, and size. This task requires a highly interdisciplinary effort among chemists, physicists, biologists, material scientists, and engineers. From a technology and applications standpoint, the unique properties at the nanoscale result in extraordinary characteristics at the macroscale. The impact areas are vast, ranging from consumer products such as construction materials, textiles, and cosmetics to electronic devices such as memory sticks and sensors.

Five years ago, recognizing the immense potential of nanoscience and nanotechnology, the Federal Government initiated the National Nanotechnology Initiative to help coordinate and focus multiagency investment in these areas. The Department of Defense (DOD), the Department of Energy (DOE), the National Aeronautics and Space Administration (NASA), the National Institutes of Health (NIH), and other mission-driven agencies began to view nanoscience and nanotechnology as strategic opportunities to revolutionize the way future missions are conducted and potentially enable missions that are currently not feasible. Space exploration missions, in particular, are among the most difficult and most dependent on advanced technology. Nanotechnology products that could provide future space missions with unprecedented capability include smart materials (materials engineered on the nanoscale to perform a specific function), more selective and sensitive sensors, high-density electronic devices, and miniaturized spacecraft systems (e.g., microcraft and robots).

GOALS OF THE WORKSHOP

The participants in this NNI Workshop on Nanotechnology in Space Exploration included DOD, NIH, NASA, DOE, and the National Science Foundation (NSF), with NASA providing leadership for the execution of the goals of the workshop. The workshop was divided into six sessions that discussed the following areas:

- Nanomaterials
- Nanosensors and instrumentation
- Microcraft
- Micro/nano-robotics

- Nano-micro-macro integration and nanomanufacturing
- Astronaut health management

The objective of the workshop was to articulate for each of the above areas the following:

- Vision
- Scientific and technological state of the art
- Major challenges (barriers and solutions)
- Goals (5–10 years and beyond)

SUMMARY OF THE SESSIONS

Nanomaterials

Advanced materials will play a critical role in the realization of the goals and missions of multiple Federal agencies as well as serve to fuel the U.S. economy in years to come. This is particularly true for NASA’s Exploration and Science Missions where a reliable operation is required for long durations in the harsh space environment. Also, high-performance materials will be crucial because spacecraft resources are limited. In particular, there will be a need for lightweight and low-density materials for future space and aeronautics systems such as ultra-large apertures and solar sails, and there will be a need for materials with high strength per mass for launch vehicles and human space habitats. In order to successfully carry out missions lasting a decade or longer, conventional materials used for space vehicles and systems need to be improved with regard to performance by several orders of magnitude, a task difficult to achieve using current technologies. New concepts and approaches are required to design, develop, and fabricate materials with multiple capabilities including strength (stiffness and toughness), sensing/actuating, and self-healing. Nanoscience and nanotechnology are promising avenues toward creating new materials or improving existing ones to provide superior performance. To push forward the state of the art in nanomaterials technology, researchers must: (1) develop predictive models/simulations to guide materials and processing design; (2) achieve a fundamental understanding of synthesis and nano-macro structure growth mechanisms; (3) integrate physical and chemical forces with external fields to obtain desired properties during processing; (4) develop the capacity to control synthesis and manufacturing processes over all length scales; (5) elaborate inexpensive methods for the production (terrestrial and on other planets) of highest quality nanomaterials; and (6) tailor synthesis, processing, and characterization methods to efficiently utilize resources on Earth and on other planets.

Nanosensors and Instrumentation

It is important to capitalize on the investment within academic, government, and industrial research circles in order to develop nanoscale sensors and instrumentation that enhance existing space mission capabilities and enable new mission concepts that are prohibitive or impossible without this technology. The vision for nanosensors in space exploration covers remote sensing, vehicle health and performance, astrobiological and geochemical research, and manned space flight. Nanoscale system developers face many of the same issues encountered at the microscale concerning materials, structures, and processes. Materials include thin films and novel compounds with unique properties. Structures are not only the layering of materials, but also the three-dimensional shapes of nanocomponents and their interaction properties. Processes are the means by which materials and structures are handled in the construction of functional devices. Although the overall understanding of the physical and chemical principles governing at the nanoscale is rapidly advancing, nanotechnology’s full potential will be realized only when these fundamentals are fully understood and new laws are established. The development and use of nanoscale sensors involve several challenges: (1) production and refinement; (2) manipulation and control; (3) lithography; (4) nano-micro-macro integration; (5) toxicology; (6) robust and reliable architectures; (7) self-calibrating networks; and (8) data fusion.

Microcraft

Microcraft are defined to be, for the purposes of this document, vehicles with mass of 100 kg or less that are able to move through the environment (actively or passively), sense the environment, and communicate with human operators (directly or via relay). This definition includes conventional "miniaturized" unpiloted vehicles as well as future vehicles that might be microscopic in size. By including vehicles that may passively "float" through the environment without continuous propulsion and orbiting satellites deployed from larger vehicles, the definition of microcraft is not limited to vehicles with substantial amounts of propulsion. As a result, these vehicles do not necessarily need to overcome the extreme energy cost that propulsion at very small scales may require. By allowing communications relay, a similar extreme energy cost that may be associated with long-range communications may not impose severe constraints on these vehicles. Microcraft may have individual mass and unit costs that are a thousand or ten thousand times less than those of vehicles we use today, such as many NASA spacecraft; DOD unmanned aerial, ground, or underwater vehicles; weather balloons; or agricultural vehicles. In some cases microcraft will be able to sense as well as today's systems because nanotechnology-based sensors can be miniaturized while retaining full performance. In other cases, such as with imaging apertures, the limits set by physical laws are already constraining, but microcraft can get much closer to the target and capture images at the same or better resolution than larger conventional systems, even with a small camera aperture. Arrays or swarms of microcraft can perhaps not only sense but also affect the environment, such as deploying a net of high-strength material. For many applications, microcraft will allow comparable performance to be maintained even as the vehicle mass drops by orders of magnitude, but the real benefit of microcraft probably will be the use of microcraft constellations capable of communicating with each other and a remote center of operations/analysis.

Micro/Nano-Robotics

This workshop session explored how nanotechnology might affect, and be affected by, constructing, programming, and organizing robots at all scales down to the smallest feasible devices. The outcome of the session was a roadmap for nano-robotics.

Intelligent and autonomous robots have been envisioned since Karl Capek coined the term robot. Nanotechnology will provide new capabilities for building robots, including better materials, improved power sources with increased power density, advanced computers, and better sensors. There is reason to believe that smaller robots will be manufactured at lower cost than larger ones, providing the opportunity of deploying large collectives of small robots to solve tasks in new ways. Specific to space applications, micro/nano-robots could enable in-space inspection, maintenance, and repair. Mobile microrobots could search for life on planets by retrieving samples and performing on-board analysis. Miniature devices inside the body could monitor astronaut health during a mission. Finally, in-space assembly and construction with massively parallel micro/nano-robots and miniature manufacturing robot workstations for unanticipated needs could become possible. Three major challenges of micro/nano-robotics are: (1) miniaturization; (2) three-dimensional assembly; and (3) programming and control of a large number of micro/nano-robots.

Nano-Micro-Macro Integration and Nanomanufacturing

Nanotechnology, including the capability to engineer materials and devices from the molecular and atomic level, allows unprecedented access to phenomena at the nanoscale. The excitement of nanotechnology evokes a variety of visions of the future in which small, nanotechnology-enabled autonomous systems explore the solar system and prepare the way for human exploration of the Moon and the planet Mars. Primarily, this entails the development of macroscale systems to effectively exploit and integrate novel nanoscale capabilities without significant loss of performance. A comprehensive set of tools needs to be generated for the fabrication, assembly, testing, and characterization of these systems. Also, system developers should inculcate a fault-tolerant design approach, realizing that defects are intrinsic to large collections of nanoscale structures. Finally, the overall system should meet the stringent standards of space reliability assurance, not only by being inherently robust during exposure to a variety of adverse space environments, but also by not causing the catastrophic failure of other associated systems.

Astronaut Health Management

The ultimate vision for nanotechnology in astronaut health management is to help enable a quality of life, a quality of human performance, and a quality of medical care equivalent to that on Earth, regardless of the type or duration of the space mission. This is the vision for a large-scale, sustainable human presence in space. Nanotechnology will be the enabler for this vision for two primary reasons: first, nanotechnology products will follow the "better-stronger-lighter-cheaper" paradigm, and second, many of the challenges to astronaut health management can be related to nanoscale phenomena and must be met with solutions provided by nanotechnology. The principal mission components that are likely to benefit from nanotechnology are pharmaceutical countermeasures, self-sufficient medical care, environmental control, human factors, and radiation shielding. Application of nanotechnology for astronaut health management requires: (1) a better understanding of the basic science behind the effects of the space environment on astronauts; (2) fostering of interdisciplinary connections between researchers in different fields, including engineers, scientists, and clinicians; and (3) alternative paths for regulatory approval of drugs and devices for economically viable research and development.

CONCLUSIONS

The workshop participants concluded that nanoscale science and technology will impact many areas of interest to multiple Federal agencies and will lead to the following:

Near- to Mid-Term (5–10 Years)

- New lightweight materials with superior strength compared to conventional ones, useful for space and aeronautic systems
- New adhesives and thermal protection materials
- Materials with enhanced radiation protection, including the capability of measuring radiation (embedded radiation dosimeters)
- New electronic components and high-density memory devices
- Ultra-sensitive and selective sensor devices
- New materials for vehicle and human health management

Long-Term (Beyond 10 Years)

- New fault-tolerant computing and communication technologies
- Microcraft for autonomous exploration
- Multifunctional materials offering thermal, radiation, and impact resistance
- New approaches for energy generation, storage, and distribution
- Hierarchical systems exploiting developments in biotechnology, information technology, and nanotechnology
- Environmentally friendly methods for biomimetic material synthesis

1. INTRODUCTION

Meyya Meyyappan and Minoo Dastoor

BACKGROUND

Ever since man started taking control of the environment and shaping things to meet human needs, he has endeavored to understand matter at its fundamental level. Since the dawn of the 21st century it has become possible to study, design, and synthesize structures with the precision of one-billionth of a meter (nanometer). Nanoscience is the study of the fundamental principles of matter at the scale of ~1–100 nm, while nanotechnology is the application of such knowledge to making materials and devices.

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Five years ago, recognizing the immense potential of nanoscience and nanotechnology, the Federal Government initiated the National Nanotechnology Initiative to help coordinate and focus multiagency investment in these areas. DOD, DOE, NASA, NIH, and other mission-driven agencies began to view nanoscience and nanotechnology as strategic opportunities to revolutionize the way future missions are conducted and potentially enable missions that are currently not feasible. Space exploration missions, in particular, are among the most difficult and most dependent on advanced technology. Nanotechnology products that could provide future space missions with unprecedented capability include smart materials (material engineered on the nanoscale to perform a specific function), more selective and sensitive sensors, high-density electronic devices, and miniaturized spacecraft systems (e.g., microcraft, robots).

This report on nanotechnology in space exploration is one of a series of reports resulting from topical workshops convened during 2003 and 2004 by the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the National Science and Technology Council’s Committee on Technology through the National Nanotechnology Coordination Office (NNCO). This workshop was convened to gain input from stakeholders in the field of nanotechnology on the enabling capabilities and products that could impact robotic and human exploration of space. The objective of the workshop and this report is to provide guidance on the research and development priorities for nanotechnology for space exploration.

THE WORKSHOP

The participants in this NNI Workshop on Nanotechnology in Space Exploration included DOD, NIH, NASA, NSF, and DOE, with NASA providing leadership for the execution of the goals of the workshop. The workshop was divided into six breakout sessions that discussed the following areas:

- Nanomaterials
- Nanosensors and instrumentation
- Microcraft
- Micro/nano-robotics
- Nano-micro-macro integration and nanomanufacturing
- Astronaut health management

The objective of the workshop was to articulate for each of the above areas the following:

- Vision
- Scientific and technological state of the art
- Major challenges (barriers and solutions)
- Goals (5–10 years and beyond)

The workshop was held in Palo Alto, CA on August 24-26, 2004 and drew nearly 200 attendees from academia, industry, and Federal laboratories. The workshop started with a plenary session featuring keynote talks from top Federal Government officials and visionary presentations from researchers in the field. Following this, breakout sessions on the six topics were held for a day and a half. Each breakout session included several presentations from pioneers in the subject matter and in-depth discussion to prioritize research needs and identify barriers and solutions. On the final day, participants in each breakout session started outlining the contents of this report.

The findings from this workshop were taken into consideration in preparation of the updated NNI Strategic Plan released in December 2004[1] and were used as input to the development of programs that make up portions of the fiscal year 2006 and 2007 NNI budgets requested for the National Aeronautics and Space Administration and other NNI participating agencies.[2]

THE REPORT

The report presents the ideas and recommendations for future research and development that were generated by the breakout groups. Chapters 2-7 review the technology challenges and research needs unique to each of the breakout session topics, including an overview of the current state of the art, goals and challenges, visions for the future, recommendations for future nanoscience research, and suggested implementation strategies to accelerate the development of important technologies. Appendices include the workshop agenda, a list of workshop participants and report contributors, and a glossary.

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[1] http://www.nano.gov/NNI_Strategic_Plan_2004.pdf.

[2] See: http://www.nano.gov/NNI_06Budget.pdf and http://nano.gov/NNI_07Budget.pdf.

2. NANOMATERIALS

Breakout Session Co-Chairs: James O. Arnold, Mike Meador, and Mia Scochi

VISION

Reliable and durable materials used for the manufacture of space vehicles are crucial for successful exploration missions of long durations in the harsh space environment. Future Crew Exploration Vehicles (CEVs), habitats, microcraft, space suits, and other space systems will be constructed using high-performance, smart materials. Nanomaterials will be developed that are capable of serving several functions, including tolerating high mechanical stress/strains, monitoring vehicle condition, as well as storing and delivering electrical power. Of particular interest to space missions are strong, lightweight, low-permeability materials for cryogenic propellant tanks, and micrometeoroid-resistant, highly insulating, and radiation shielding materials for space vehicles and habitat structures. Approaches using self-assembly, as opposed to picking and placing individual atoms, could be utilized to create a myriad of systems ranging from self-healing structural components for vehicles and habitats to fault-tolerant sensors and electronic circuits. In general, self-assembly may be defined as the thermodynamically driven, self-regulating process by which supramolecular structures form due to information programmed in the original components. Supramolecular structures could be designed to be dynamic and reversible and to have an inbuilt capacity for error correction, sometimes referred to as self-healing. Astronauts' extra-vehicular activity (EVA) suits should be made of lightweight and flexible materials providing adequate mobility and dexterity while providing insulation and shielding from radiation.

Highly efficient and lightweight power systems capable of tolerating wide ranges of operating temperatures are also envisioned to play an integral role in future exploration missions. Equipment central to space missions, such as communication devices, scientific instruments, computers, and robotic systems, will be based on molecular electronics. Lightweight, handheld analytical instruments will be used to analyze samples from planetary soil and the atmosphere, providing information about biological activity and chemical composition. In this vision, storage and encryption of the mission's compiled data files will be enabled using high-density, lightweight memory devices. Monitoring the crew's health during missions is another high-priority area. Astronauts will use handheld devices capable of detecting disease-causing organisms from a single blood sample. Detailed discussion about sensors is provided in Chapter 3 of this report.

Nanoscience and nanotechnology are expected to provide materials with enhanced durability and performance compared to conventional materials. Nanomaterials will also play an important role in the development of ultra-sensitive and selective sensors. The ability to design and manufacture nanomaterials could therefore radically change the way in which future long-duration human and robotic exploration missions are conducted.

STATE OF THE ART

The unique properties of nanomaterials and nanostructures have inspired materials scientists in recent years. Nanotechnology is already being used to improve the performance of existing products (e.g., water- and stain-resistant materials for clothing, light-sensitive coatings for glasses, and UV protection in cosmetic products). To shed some light on how and why nanomaterials could improve space mission performance, a short summary is provided on current technological status.

Bioinspired Materials

Hybrid materials could be used in the fabrication of cellular hierarchical structures with self-healing, sensing, and actuation functions [4, 5]. The design approach allows for the incorporation of a range of functionalities [6, 7], such as nanowhiskers, nanotubes, nanowires, and nanoplates. As an example, reinforced polymer matrix composites made from clays or exfoliated graphite could be used [1–11]. Nanocomposites with self-healing functions could be developed by utilizing the self-assembling characteristics of micellar and colloidal systems (Fig. 2.1). In addition, self-assembly could allow for low-cost fabrication of complex nanostructures and is an essential component of practical, nanoscale fabrication. Further, miniaturized sensors and actuators could be embedded into materials in order to impart smart functions. Piezoelectric microcantilevers or nanotubes (e.g., BN/C and $PbO{\cdot}ZrO_2{\cdot}TiO_2{\cdot}$[PZT]) could be used as embedded actuators.

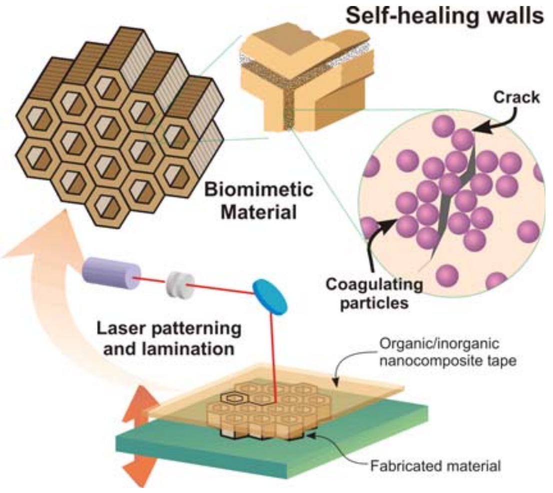

Figure 2.1. Laser patterning and subsequent lamination of organic-inorganic nanocomposite tapes is one method that will be used to produce cellular biomimetic materials. Self-healing functions are introduced through the manipulation of colloids at defect sites (© 1997 Nature Publishing Group; reprinted by permission from [5]).

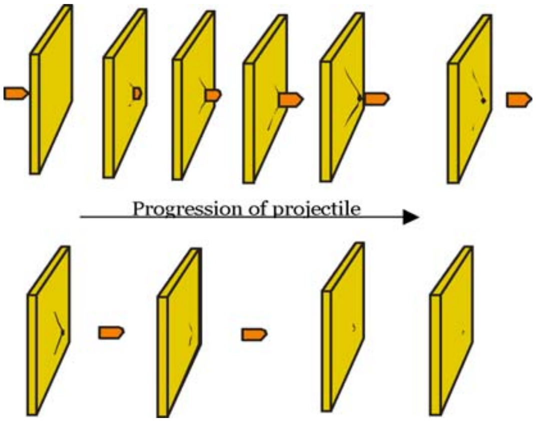

Figure 2.2. Depiction of damage tolerance via self-healing material (courtesy of NASA).

Characteristics of natural materials, such as self-healing and self-assembly, bring new meaning to the concept of material design. Based on these features, it may be possible to design materials capable of instant self-repair from penetration of projectiles such as fast-moving micrometeoroid debris or a bullet (Fig. 2.2). This capability would provide a route to manufacturing of space vehicles, crew habitats, and other space systems that require less human attention during the exploration mission. Such self-sustainable materials could prove advantageous for space vehicles in providing adequate shelter against the hostile space environment and for deployable structures for scientific data collection.

Aerogels

Low-density, highly porous, and low thermally conductive materials such as aerogels are attractive materials for a variety of aerospace applications. However, the use of aerogels in aerospace components has been limited to date due to their poor mechanical properties and low durability. In addition, the processing of conventional aerogels requires the use of supercritical fluid drying, which increases manufacturing costs and limits component size. New polymer cross-linked aerogels have been developed at the NASA Glenn Research Center to overcome some of these disadvantages (Fig. 2.3). These low-density (< 0.2 g/cm^3) aerogels have 300 times higher flexural strength than conventional silica aerogels, and yet they are thermally insulating (< 40 mW/mK). Furthermore, these materials exhibit specific compressive strengths 10 times that of steel and equivalent to that of fiber-reinforced composites. While densities and thermal conductivities of these aerogels are three times that of conventional aerogels of similar density, recent work has shown that it is possible to significantly reduce density and thermal conductivity while still maintaining superior mechanical properties.

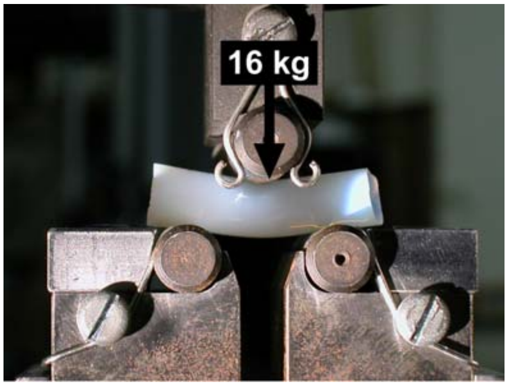

Figure 2.3. Polymer cross-linked aerogels have 300 times the flexural strength of conventional aerogels and specific compressive strengths 10 times greater than steel (courtesy of NASA).

Conventional aerogels are composed of individual silica nanospheres joined by fragile necks forming a "pearl necklace." Each silica nanobead has pendant hydroxyl groups. At NASA Glenn Research Center, these hydroxyl groups have been reacted with organic monomers (e.g., isocyanates), to produce conformal coatings around the nanospheres and necks. As a result, these new aerogels do not collapse during solvent evaporation and can be processed on the bench-top without the use of expensive supercritical fluid drying. New aerogel formulations have also been developed to render the material flexible. Furthermore, the chemistry has been modified to create polyimide, epoxy, and polystyrene cross-linked silica aerogels, as well as polymer aerogels made from a variety of metal oxides. Potential applications include insulation materials for cryogenic propellant tanks and EVA suits.

Materials to Address Future Entry Vehicles

NASA's space exploration plans involve the development of a Crew Exploration Vehicle whose function includes Earth atmospheric entry for returning astronauts from the Moon and subsequently from the planet Mars. For these missions, the CEV re-entry heating rates are on the order of factors of ten and forty times, respectively, more severe than those on the wing leading edge of the Space Shuttle [12]. NASA's exploration missions in the future will be of long durations, and hence will involve extended exposure to radiation and to micrometeors and orbital debris (MMOD). This, in turn, will increase the risk of damage to the space vehicle and to human safety. Because such an exposure grows linearly with flight time, there is an urgent need to develop strong and durable materials for space vehicles. Advances in nanotechnology have led to new concepts for the development of a single shield that can improve mission safety and performance (through mass reduction) against all three of these threats, each of which can be potentially catastrophic.

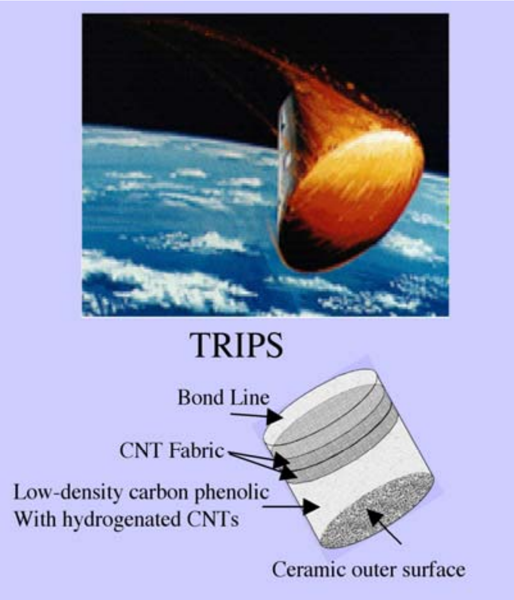

Figure 2.4. A photograph of an Apollo-style CEV. A schematic of Thermal Radiation & Impact Protective Shield. A cross sectional view of the TRIPS is shown and bonded to the substructure at the bond line (courtesy of NASA).

One concept for employing nanomaterials for thermal, radiation, and impact protective shields (TRIPS) developed at NASA Ames Research Center is illustrated in Figure 2.4. The CEV's thermal protection system (TPS) that protects the vehicle from intense aerothermal heating also provides radiation protection if the materials constituting the heat shield are chosen wisely. Materials with high concentrations of hydrogen and carbon are good candidates for radiation shielding (e.g., polyethylene is a material of choice for radiation shield designs because less secondary radiation is produced during the collision process with high-speed cosmic rays and solar event particles). Analysis suggests [12] that the use of fully dense carbon phenol for a CEV TPS could provide simultaneously 50–70 percent of the radiation shielding as well as adequate thermal protection needed for a year's duration in space, a typical round-trip time for a Mars mission. TRIPS would embody a carbonaceous, single-use ablator material whose origin would be a mid-density material based on existing fully dense carbon phenol (the Galileo entry probe heat shield material) or the phenolic impregnated carbon ablators (PICA) flying on the Stardust Return Capsule. The TRIPS material also incorporates hydrogenated carbon nanotubes (CNTs), adding radiation shielding. Orientation of the CNTs could lead to lighter TPS by acting as passive heat pipes to hot spots across TPS acreage and/or to heat sinks on the CEV [13]. As shown in Figure 2.4, a third shielding function could be implemented by the use of a built-in MMOD shield similar to that being developed for flexible space habitats [14]. Here, a hard ceramic outer shell of the fabric serves to break up MMOD strikes.

MAJOR CHALLENGES

Barriers and Solutions

What must be done to advance nanotechnology from its current state, generally Technology Readiness Level (TRL) 1–2 (discovery of a phenomenon), to TRL 4–5 (demonstration of devices in a simulated space environment), to TRL 7–8 (mission insertion)? Large-scale production methods must be developed to produce a variety of nanomaterials (e.g., nanotubes, nanowires, quantum dots, nanoparticles, self-assembled materials) with controlled purity, size, and properties. The utility of nanostructures cannot be evaluated and realized when consistency in their purity and properties is absent. Furthermore, while the properties that are of interest are at the nanoscale, many applications require that such characteristics translate into radical changes in performance at the scale of larger space structures. Nanomaterials must be producible with controlled morphology and structure over a variety of length scales to enable the fabrication of a diverse range of components from nanometer-sized devices to large-area (hundreds of square meters) optical arrays or antennae. Exploration missions will require the ability to produce a wide assortment of nanomaterials using resources (raw materials and power) available on other planets. In order to produce such nanomaterials within the hostile operational environments of other planets, a thorough understanding of production conditions is first required in the more benign terrestrial environment. Finally, these materials must be able to withstand the rigors of space flight from launch to the end of the mission. Materials used in space missions will experience harsh environments (e.g., extreme temperatures, radiation, thermal cycling, caustic/reactive atmospheres). The individual and synergistic effects of these conditions on the durability and performance of advanced materials is a critical concern for these important mission applications.

While advances in nanotechnology are making strides to address these requirements, two challenges exist that prevent the full realization of the use of nanomaterials in future space missions:

- Control the synthesis and assembly of functional materials from nano- to macroscales in a reliable and consistent manner
- Demonstrate that prolonged (> 10 year) human and robotic exploration missions can be reliably executed utilizing nanotechnology-based materials, devices, and systems

Technical Barriers

Nanomaterial Production in Bulk Quantities

The development of nanomaterials, the implementation of their existing functions, and finally their manufacture, are challenging tasks. Much work is needed with respect to the extent of control and consistency of material synthesis and assembly in order to meet the challenges described above. Nanomaterials development is still in its infancy, and as a result, control of the synthesis, assembly, and processing of nanomaterials is still a challenge. A barrier to producing nanomaterials in bulk quantities is the lack of understanding and control of the mechanisms that govern the growth of the structure from nanoscale to micro- and macroscale. Hierarchical multiscale approaches are needed to model and simulate these growth processes. The resulting models could predict the effect of changes in processing methods on morphology, structure, and ultimately, properties and durability. A better understanding of the effects of external forces (electrical or magnetic fields) on the alignment and processing of nanomaterials is also required in order to produce controlled structure and morphology. For example, even the most elaborate manufacturing protocols for carbon nanotube fabrication yield less than 100 grams of pure material per week.

Production of Pure and Uniform Nanomaterials: In Situ Characterization

An important issue regarding the production of nanomaterials is the evaluation of their quality. This calls for the development of reliable and cost-effective analytical protocols that are compatible with the manufacturing process. Such protocols will require a multipronged approach, including a suite of new instruments capable of fully analyzing material behavior *in situ*; tools to manipulate, position, and probe specimens with nanometer-scale resolution; and a comprehensive theoretical understanding that correlates the behavior on the atomic scale with that at the micro/macroscale. Advanced characterization tools are required to monitor *in situ* the growth and properties of nanomaterials and to evaluate their characteristics and micro/nanostructure non-destructively. The primary goal is to minimize the time invested in instrument set-up, sample preparation, calibration, and measurement while still providing reliable, quantitative data. In order to accomplish this goal, instruments must be redesigned such that the tool functions *in situ* without destroying the product in the process. For example, many nanoscale devices comprise multiple thin layers, and measurement of properties at buried interfaces is critical. For these materials, non-destructive approaches capable of real-time, *in situ* characterization are ideal. However, spatial resolution must still be addressed, giving the user the opportunity to probe the device-under-test in such a way as to provide key information on minute regions of a specimen with extremely precise registration. Finally, decision-making processes at the managerial level will need to be streamlined to ensure an efficient production environment.

To illustrate this issue, synthesis of carbon nanotubes yields a broad range of different nanocylinders in terms of their dimensions and chemical composition (e.g., diameter, length, chirality, twist), resulting in a broad range of electronic and physical properties. Hence, reliable probes are needed to monitor and sort the structures of specific characteristics.

Nanomaterial Stability and Duration

Durability of materials is a critical issue for any space mission. Materials used in applications to support these missions must survive a wide variety of threats, from extremes in temperature to different types of radiation to caustic planetary atmospheres. Unlike other applications for nanomaterials, materials used in exploration missions must perform reliably and survive these threats for many years, even decades, without the need for continuous repair or replacement. A detailed understanding of the individual effects of these threats on the long-term durability and performance of advanced materials is essential to their effective use in exploration missions. The synergistic effects of two or more of these threats, e.g., radiation damage and thermal cycling, must also be explored. Accelerated test methods and analytical models must be developed not only as a screen for new materials, but also as predictive tools to determine useful service lives for these materials. Protective schemes must be developed to minimize the impact of these environmental exposures on materials integrity, durability, and performance. Materials with the capabilities of self-diagnostics and self-healing must be developed since the resources and opportunities for repair on these missions will be limited.

Solutions

1. Refocus and expand collaborative efforts by developing partnerships including appropriate NNI members, NSF, NASA University Research Education Technology Institutes (URETIs), and industry on the first two barriers listed above. NNI partners should include NASA, the National Institute of Standards and Technology (NIST), DOE, and DOD. The synergy between experiment and theory is critical to breaking the nano-macro synthesis and assembly barrier and is also a key to developing the life prediction tools and techniques specified earlier. Also, as mentioned elsewhere, partnering with experts from the biological sciences would be beneficial. This is illustrated clearly by the example cited above about learning from nature how to create self-healing nanostructures.
2. In addition to being mainly a NASA, DOD, and DOE (nuclear facility) problem, radiation effects are important even today in commercial electronic devices such as laptop computers. The small efforts to date looking at radiation effects on nanomaterials should be increased and should more strongly engage existing NASA and DOD capabilities. In the area of electronics, these effects may become more important as feature sizes shrink to the nanoscale. New NASA/DOD/electronics industry partnerships addressing radiation effects on nanotechnology-based computing and memory could hasten the development of solutions.

Programmatic Barriers

The development of nanotechnology-based products demands high levels of expertise and coordination among participating Federal agencies, which calls for a sustained funding source. Secondly, adoption of new nanomaterials into various functions of space missions in place of existing space-qualified materials may run the risk of schedule delays and budget overruns.

Solutions

A sustainable funding source from the government and/or the private sector is necessary to advance research and development. In addition, research programs need to be focused and targeted to solving specific problems. Federal mission needs and interests have to be clearly articulated in the form of goals and reasonable timelines, and budgets need to be allocated so that milestones can be reached. Prior to systematic planning, the value of nanotechnology to space missions needs to be identified. To that end, the following steps are suggested:

1. In addition to a capability assessment that has recently been completed, systems analysis is currently being conducted to understand the impact of nanotechnology on science and exploration missions to formulate a capability roadmap for NASA. Such analysis should be carried out across a broad range of missions at the agency level with the participation of experts in nanotechnology at both the research and the space flight centers. Factual estimates of return on investment can then be used to guide management's near- and far-term budget allocations. Federal agencies should make an attempt to increase their funding base by leveraging investments in nanotechnology towards developing strategic partnerships with selected industrial players who share common interests.
2. The adoption of emerging technologies in space missions has always been an issue. As mentioned above, the first step toward a solution to this issue involves a thorough systems analysis. Secondly, every launch opportunity available needs to be taken advantage of in order to minimize costs while maximizing experimental output. A good example of this is the use of nanosensors on a U.S. Navy Delta rocket flight in a NASA Ames/Goddard project. Also, the agency needs to periodically brief project managers and higher authorities on the usefulness of nanotechnology in various aspects of space missions and its advantages over conventional technologies. Continuous communication and demonstrations via systems analysis are important steps toward achieving the first space flight equipped with nanotechnology-based materials.

GOALS

5–10 Years

- Develop models for design and processing of nanomaterials. Multiscale physics-based models will be developed and used to predict and simulate the effect of processing conditions and materials composition on the nanostructure's growth and architecture. Simulations and predictive tools are currently being developed for the processing of carbon nanotubes and polymer-clay nanocomposites. These new tools will allow for the simulation of structures covering a wide range of length scales, i.e., from a few nanometers through micrometers to macrostructures.
- Develop interfacial chemistries. Chemistries that stabilize the interfacial bonding between the nanomaterials and the bulk material (matrix) will be developed. Current efforts include functionalizing CNTs, aerogels, and clays. Processing methods will be optimized in order to provide a strong and stable interface.
- Develop improved CNT nanocomposites. This thrust area will focus on: (1) processing development of CNT nanocomposite materials tailored to applications such as crew habitats (flexible nanocomposites) and space suits (fibers and woven fabrics); (2) scaled-up fabrication of CNT nanocomposites and validation of the material; and (3) developing silicon carbide nanotubes (SiCNTs). Silicon carbide is found to be stable at temperatures exceeding 1000°C,

whereas carbon is limited to 600°C. Therefore, a SiCNT nanocomposite holds promise to survive in a high-temperature environment (e.g., extreme space and planetary environments).

- Develop biologically inspired materials. NASA plans to continue current efforts that aim at exploring natural phenomena and materials, including but not limited to cell membranes, bone, nacre, spider silk, etc. The goal is to discover novel biological materials, mimic desired properties (e.g., strength, toughness, self-assembly, and self-healing), and finally create new biologically-inspired nanomaterials.
- Develop high-throughput methodology for nanomaterial design. The pharmaceutical industry uses combinatorial chemistry and high-throughput screening of a large pool of molecules in its search for drug candidates. In the search for a "rational design" of a nanomaterial, analog combinatorial methods could be developed to generate a wide variety of candidate nanomaterials, followed by high-throughput screening. The fully developed protocol would incorporate chemical analysis and validation steps in which the experiments would be performed in concert with multiscale design and simulations. The "rational design" methodology for materials is a rather new concept but has already started to show promising results.
- Develop tools to predict and detect material failure. As mentioned in previous paragraphs, material durability is of concern and therefore a priority topic within the space research effort. Failure detection and life prediction methods exist for conventional materials, although they are not always applicable to extreme (harsh) environmental conditions. New tools and protocols for evaluating material stability and durability need to be developed that account for harsh conditions such as extreme temperatures, radiation, dust abrasion, and chemicals. Development and testing can be accomplished within the next five years by modifying current protocols. In the future (beyond five years), these methods will be improved further to cope simultaneously with different hazardous conditions. In addition, these newly developed tools and methods need to be adapted to nanomaterials because the current ones may not have the capacity to detect failure and stability at the nanoscale.
- Develop a fundamental understanding of mechanisms that govern the growth of nano-macro structures. It is reasonable to expect that the efforts outlined in the state-of-the-art paragraphs will progress, and within the next 10 years a good understanding of nanomaterial growth processes will be attained. This enhanced understanding will enable the identification of the means to control nanostructure synthesis and growth over a wide range of length scales.
- Develop real-time methods to characterize nanomaterials during processing and/or synthesis. Characterization tools are critical to the development of processing methods with precise control of nanostructure and morphology. These tools must be capable of providing chemical and structural analysis in real time to be able to impact manufacturing processes. Ongoing research sponsored by NASA, NIST, and other Federal agencies can lead to the development of these methods within the next ten years.
- Develop bioinspired, self-repairable materials with damage tolerance and sensing characteristics.
- Develop quantum devices for computing and power generation.

Beyond 10 Years

- Develop procedures to manipulate physical and chemical forces involved in material synthesis and growth over all length scales. Manipulation of the growth mechanisms for nanomaterials by altering processing conditions (temperature, pressure, flow rate, chemical composition) is routinely employed to modulate chemical reactions in the synthesis and growth of nanomaterials. Some research has focused on the use of externally applied fields (e.g., magnetic fields) to provide further control of nanostructure and morphology development. However, further work is needed in this area to develop a “chemistry and processing toolkit” to produce a variety of nanomaterials with desired size, structure, and properties. Complete integration of chemical, physical, and external forces during the processing of nanomaterials is essential to producing large-scale structures for vehicles and habitats. This integrated capability can be developed by building upon previous successes in understanding the mechanisms for growth and nanostructure development in nanomaterials and on the use of advanced characterization techniques for real-time monitoring of chemical processes and nanostructure development in the synthesis and processing of these materials.

- Develop methods to produce high-quality nanomaterials using extraterrestrial resources and adapt synthesis, processing, and characterization methods to conditions in space.
- Utilize resources (raw materials, power, etc.) that are available on a given planet or in space for the synthesis and processing of nanomaterials. This is critically needed for exploration missions. Current efforts for *in situ* resource utilization have focused on the synthesis and production of conventional materials. These methods will require some additional work to make them suitable for use in the production of nanomaterials.
- Apply technology infusion for multifunctional, self-healing materials for space and terrestrial applications.
- Develop bioinspired power sources such as bio-nano batteries.

CONCLUSIONS

Nanomaterials will enable future space missions with greatly increased performance and affordability because of their outstanding abilities to function in harsh environments and in severely resource-limited applications (mass, power, volume, etc.). For example, one can envision vehicle structures made of high-strength, ultra-lightweight, and functional materials (e.g., tolerating mechanical strain/stress) delivering electrical power and continually reporting on material status to an Integrated System Health Management (ISHM) subsystem. Each ISHM sensor will have powerful localized computing capabilities, while the central processor they communicate with will have logic/memory performance comparable to today’s largest ground-based computers. The ISHM sensors and electronics will owe their powerful capabilities to the development of nanomaterials. Human and robotic space exploration vehicles will be fitted with lightweight, multifunctional, nanomaterial-based shields, with a mass that is a fraction of what is currently employed, to protect the assets and crew against the multiple threats (atmospheric entry heating, radiation exposure, and micrometeorite/orbital debris impact) associated with deep space missions. Smart nanomaterials will provide similar safe-haven benefits for astronaut habitats and space suits (including enhanced mobility and dexterity). In addition, nanomaterials will provide exceptionally effective sealants for propellant cryotanks against the most penetrating of reagents such as hydrogen gas. Finally, nanomaterials will enable the fabrication of power systems with augmented power output and density capable of operating faultlessly at extreme temperatures in space.

The vision is to fulfill the promise of nanotechnology across multiple materials applications; the benefits of which will match or exceed those of materials used in the past, including miniaturization of electronic devices to the microscale and the development of carbon fiber composites. The key to realizing this vision is a strong partnership between government, academia, and industry (see Fig. 2.5). A successful partnership requires the formation of a highly interdisciplinary team composed of skilled experimentalists and theoreticians with backgrounds across diverse disciplines such as physics, chemistry, biology, materials science, and engineering.

Mission managers need to be included on these teams to provide insight into mission needs while keeping themselves abreast of new technological developments.

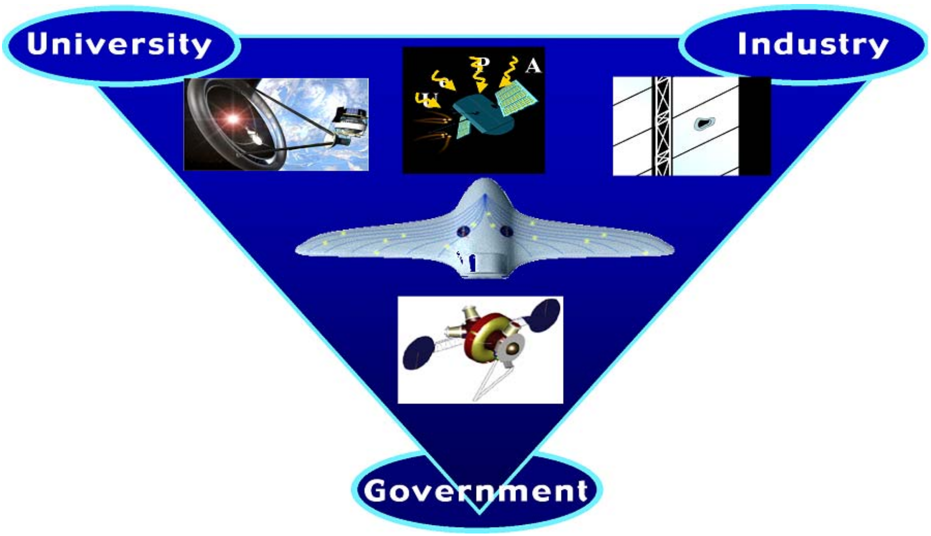

Figure 2.5. Model of collaboration required to accelerate the development of nanotechnology relevant to space missions (courtesy of NASA).

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3. NANOSENSORS AND INSTRUMENTATION

Breakout Session Co-Chairs: Sean C. Casey, Pedro Medelius, Peter Shu,
Benny Toomarian, and Mary Zeller

VISION

Advances in nanotechnology are expected to enable and enhance both supporting and mission-critical technologies in the near future. These advances will be critical in meeting the challenges of new space missions in the decades to come. The vision is to *capitalize on the investment within academic, government, and industrial research circles and to provide nanoscale sensors and instrumentation that enhance existing space mission capabilities while enabling new mission concepts that are prohibitive or impossible without this technology*. The vision for nanosensors in space exploration includes applications to remote sensing, vehicle health and performance, astro-biological and geochemical analysis, and manned space flight.

Nanotechnology is expected to provide important, mission-critical components for next-generation aerospace/astronaut sensors and instrumentation. For the last 40 years, researchers in microelectronics, chemical synthesis, and biology have pioneered novel top-down and bottom-up manufacturing, characterization, and manipulation technologies. The synergy of these technologies is the basis for a growing industrial revolution in nanotechnology. Nanotechnology offers a potential reduction in payload mass compared to similar Apollo-era systems with a consequent increase in performance. Mission engineers developing next-generation technologies for the exploration of space should consider the potential operational improvements offered by a nanoscale approach.

Following the incorporation of microelectromechanical systems (MEMS) technology in current mission concepts over the past 25 years of academic and industrial partnerships, space missions expected to benefit from critical nanotechnology enhancements will probably have launch windows from 2015 to 2025 and beyond. This understates the normally long lag-time to advance from proof of concept to a flight-ready system. It is therefore essential for current research and development efforts to continue over the next 10 to 15 years with a focus on mission-enabling technologies. The envisioned return on investment falls into several areas: bulk materials production, novel sensors, standardized integration, compact biological research laboratories, next-generation vehicle sensor systems, and rapid technology infusion.

Bulk Materials Production

The low-cost bulk fabrication of CNTs and other inorganic and organic nanostructures or their hybrids with selected properties will facilitate their large-scale use in sensor systems throughout the aerospace industry. Facilities will refine nanomaterials based on desired physical and electromagnetic properties.

Novel Sensors

Nanoscale devices are expected to exhibit quantum phenomena at elevated temperatures. Sensor developers will therefore employ capabilities previously attainable at only very low temperatures. Nanoscale devices will necessarily operate at natural frequencies within the 100 MHz to 1 GHz range. To be viable, however, nanosensors for use in space instruments should have both higher sensitivity and a higher operating temperature than current devices.

Standardized Integration

The development of nanoscale interface techniques will facilitate the rapid integration of nanodevices into conventional electronics and applicable devices. The incorporation of ancillary components such as power supplies, processors, and wireless connections will reduce the number of connections between the nanoscale and the macroscale worlds. A fully integrated system of sensors, processors, and network infrastructure could generate a palm-sized space probe.

Compact Biological Research Laboratories

Current space missions are designed to visit the distant planets and moons of the solar system in a search for the signs of life. It is unknown whether the signature of life exists in a fossilized record, in *a priori* chemical building blocks, or in some other form, if at all. Should the signature consist of fundamental chemical components, the *in situ* capability for nanoscale manipulation and analysis may be an essential research tool. Space-qualified analysis systems on board can provide the necessary selection criteria for subsequent sampling missions and more detailed laboratory analysis. In the search for biochemical building blocks within the solar system, nanoscale sensors in a chip-based format may be essential for evaluating the potential for extraterrestrial life if not also its form and function. Similar laboratory sensors should also be relevant to spacecraft environmental monitoring and control (e.g., water-quality management) and astronaut health and safety (e.g., biochemical monitoring of blood, urine, etc.).

Next-Generation Vehicle Sensor Systems

With future missions to the Moon and Mars, next-generation sensors must monitor the condition of critical vehicle systems and crew environments. Most current systems have limited monitoring capabilities because comprehensive sensor systems are prone to failure and require labor-intensive maintenance. In general, existing sensor systems do not assist in the recertification of spacecraft following each mission. A manual inspection of flight-critical hardware is an identified bottleneck in the return-to-flight process. Comprehensive diagnostics of vehicle health necessitate increased sensor reliability, durability, and coverage. Embedded or integrated sensing technologies that form a distributed vehicle nervous system are envisioned for next-generation programs. Networked sensor technologies provide *in situ* vehicle diagnostics along with a framework for active corrections and feedback control on board. With minimal size, weight, and power requirements, nanosensor networks could enable smart, self-healing vehicle designs. Embedded sensors should be stand-alone, self-calibrating, and self-regulating systems complete with signal conditioning, power, and communication capabilities. Combined with future information systems technology, embedded micro- and nanoscale sensor networks could form the critical capability needed to improve mission performance while monitoring and accommodating unexpected subsystem-level failures.

Rapid Technology Infusion

Novel sensors should be included in the early phase of the design of next-generation vehicles rather than as a forced-fit afterthought. Experience shows that technology managers should carefully partner experts on nanotechnology and sensor systems with end users so new approaches can rapidly win the support of the aerospace community. It is in providing new capabilities that nanosensor technology can revolutionize future missions through savings in weight, power, volume, and performance.

STATE OF THE ART

Working at the nanoscale, researchers have demonstrated improved devices. Workshop participants summarized current efforts and outlined areas needing improvement.

Chemical Sensors

Researchers from several Federal agencies and university research facilities are concerned with sensors for emission monitoring, fuel leak detection, fire detection, and environmental detection of hydrocarbons and hydrazine. Dr. Gary Hunter from the NASA Glenn Research Center discussed the development of sensors based on micromachining and microfabrication technology and the use of nanocrystalline materials. The performance of nanoscale sensors must improve upon existing solutions in the following areas:

- Response time, sensitivity, selectivity, and stability
- Power, packaging, signal conditioning, and communication
- Ease of deployment, reliability, redundancy, and orthogonality

The development of a lock-and-key sensing geometry at the nanoscale may enable the identification of unique electrochemical molecular signatures.

Dr. Pedro Medelius (ASRC Aerospace Corporation) reported on efforts aboard the Space Shuttle to improve leak detection using several compact spectrometers as an “electronic nose.” An electronic nose experiment from the Jet Propulsion Laboratory (JPL) flew on STS-95 in 1998 (http://enose.jpl.nasa.gov). Dr. Sudipta Seal (University of Central Florida) reviewed the performance of sensors based on doped nanostructured SnO_2 oxides integrated into a MEMS device [1]. Recent developments include the use of doped SnO_2 nanofibers grown at NASA Ames Research Center (ARC) and characterized using focused ion beams and high-resolution transmission electron microscopy (TEM). Nanofibers are gaining attention because of their high surface-to-volume ratio, preferred grain orientation, and alignment of vacancies for conduction [2]. Dr. Jing Li at NASA Ames has developed a carbon-nanotube-based chemical sensor that works on the basis of conductivity change upon exposure to gases and vapors. The detection capability for various gases is in the range of parts per billion [3].

Dr. Nicholas Prokopuk (Naval Air Warfare Center) discussed the development of nanogap architectures (1–5 nm) and their use as chemical sensors. Nanogap chemical resistors are based on the change in the electron tunneling currents with the chemical identity of the intervening target. A similar approach is used for amperometric sensors where a biological key is bound to an electrode with an electron mediator. In response to a selective biomolecular reaction, an electrical current is generated. Modifying the surface of the device controls the selectivity and specificity of these sensors. This sensing modality can be used to create arrays of sensors for high-throughput analysis and multiplexing capabilities.

Professor James Morris (Portland State) is applying his past experience with thin-film arrays of metal nanoparticles to the development of single electron transistor (SET) sensors. Optimization of a SET structure will greatly enhance the demonstrated thin-film performances of strain gauge factors in the 100s, and of ppm hydrogen sensitivity with discrimination at response times under a minute. Both examples exploit the exponential dependence of the electron tunneling current on gap width. Current research is focused on the fabrication of stable 1–2 nm islands for operation at room temperature.

Integrated Nanotube Sensors

Next-generation vehicle designers envision the integration of multifunctional materials. With the broad-based acceptance of composite materials, the potential inclusion of metallic or semi-conducting nanostructures appears both feasible and attractive. Based on the predicted strength-to-weight advantage, single-walled carbon nanotubes (SWCNTs) are the focus of studies in the use of nanotubes to make “smart” vehicle materials able to sense mechanical strain and ambient pressures and temperatures. Dr. Anthony N. Watkins (NASA Langley) described research on the handling and mechanical characterization of SWCNTs as strain-sensitive gauges. Currently, the limited availability of nanotubes with selected properties makes large-area strain-sensitive materials impractical.

Initial experiments at NASA Langley Research Center have focused on developing a CNT-based strain sensor. The fabrication steps are illustrated in Figure 3.1. Measurements indicate that CNT-based strain gauges follow commercial standards when comounted to the backside of a 2023-T3 aluminum beam. Further improvements in the CNT sensor design include new dispersion techniques for the deposition of individual CNTs, extending the design to an array of sensors, and allowing the creation of CNT-based sensors for other structural health parameters. Devices have been prototyped to demonstrate this approach to integrated and efficient vehicle-health management. Multifunctional structures that enable system-wide health monitoring and adaptive structures will fill the need for improved reliability and safety in next-generation vehicles.

CNT Cathode X-Ray Tube

Mr. Robert Espinosa (Microwave Power Technology) highlighted the use of CNTs as cold-field emission cathodes and electron sources in X-ray tubes for hand-held and portable X-ray fluorescence (XRF) spectrometers. Cold emission cathodes require less power while offering a

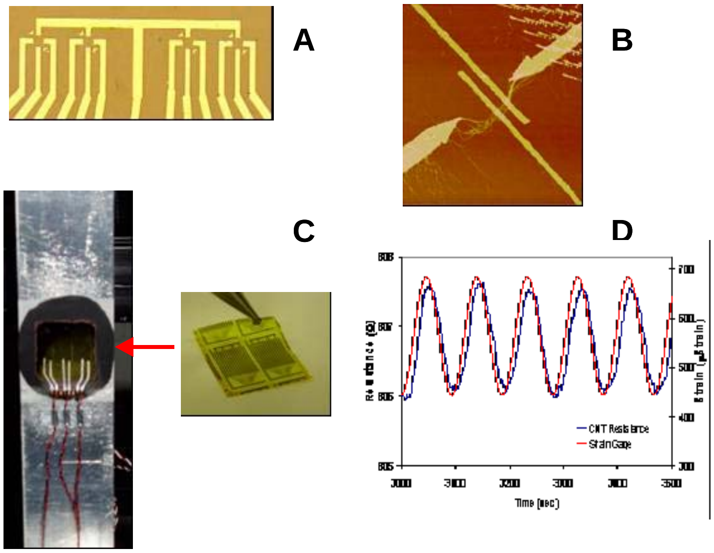

Figure 3.1. (A) Optical micrograph showing large circuit elements defined using photolithography. (B) AFM topography image detailing deposited and aligned CNT bundles spanning the alignment electrodes with the measurement electrodes defined. (C) Aluminum beam instrumented with a flexible CNT-based strain sensor and mounted in a single-axis load frame. (D) Results from the CNT strain sensor (blue) compared with a standard strain gauge (red) mounted on the backside of the aluminum beam (courtesy of NASA).

simple, rugged design. Multiwalled carbon nanotube (MWCNT) cathodes were grown via a thermal chemical vapor deposition process on substrates with metal catalysts [4]. Developed jointly by Microwave Power Technology and Oxford Instruments, the current carbon nanotubes provide an X-ray spot less than 40 µm in diameter and are suitable for X-ray diffraction (XRD) spectrometry. XRD is essential for the characterization of mineral and organic crystalline structures throughout the solar system. An XRD spectrometer based on this carbon nanotube technology is scheduled to be flown on the Mars Science Laboratory (2009) with David Blake of NASA Ames as Principal Investigator. Electron beams are also finding applications in a growing number of industrial, medical, and environmental areas (e.g., destruction of volatile hydrocarbons and biological and chemical agents). Space-related applications of CNT cathodes include purifying the air in base stations, sterilizing materials, and eliminating products such as biological toxins. CNT cold-field emission cathodes are suitable for both planetary rovers and long-duration space missions.

Nanotribology

Professor Bharat Bhushan (Ohio State University) reviewed tribology, the study of surface interactions that encompasses the complex areas of friction, wear, lubrication, and surface characterization [5]. Enabled by developments in atomic force microscopy (AFM) and frictional force microscopy (FFM), tribology has successfully addressed the nature of stiction, friction, and mechanical wear at the MEMS scale (e.g., the characterization and improvement of digital micromirror operational performance). Comparable progress is expected as nanoelectrical mechanisms are developed and their operational characteristics are studied. For many devices that involve relative surface motions, tribological studies are essential.

A research group at Ohio State University has studied material variables such as oxide and diamond-like coatings, ion implantation, self-assembled monolayers, and ultra-thin bonded perfluoropolyether lubricant films. The scaling effect of adhesion, friction, and wear have been measured and modeled. Additional studies have included the adhesion and friction of various lubricant films used in microfluidics, as well as the modeling of bioadhesion for nanoscale drug-delivery devices. In the area of biomimetics, Dr. Bhushan’s laboratory has measured the surface roughness present on lotus and other leaves and characterized the surface films to understand the mechanism responsible for high hydrophobicity. Hydrophobic laboratory surfaces are now available.

AFM tips are typically made of single-crystal silicon, silicon nitride, or diamond. Recent efforts have focused on CNT as the AFM scanning probe tip. Dr. Cattien V. Nguyen (Eloret Corporation and NASA Ames) discussed the unique mechanical properties of CNT as AFM probe tips. Existing approaches use both SWCNTs and MWCNTs. A unique fabrication process development at NASA Ames (see ref. [4] in Chapter 6) produces very robust MWCNT tips with a high aspect ratio (> 1 µm in length and 10 nm to 20 nm in diameter). In addition, a novel and simple tip sharpening technique has been developed to reduce the radius of curvature of the MWCNT tips (radius < 5 nm). As a result, CNT tips can image high-aspect-ratio features with higher lateral resolution. The nanotube tips are used in a number of different scanning probe technologies such as magnetic force, chemical force, semiconductor metrology, and liquid imaging of biopolymers. Select CNT tips are also electrically conductive and are useful for scanning probe lithography (SPL). Operated by passing an electrical current between the CNT tip and substrate while scanning, SPL can form chemically patterned surfaces with nanometer precision. With SPL, the nanotube tip offers a high-resolution and precise means for nanoscale material deposition and opens up many possibilities for nanoscale device fabrication.

Semiconductor Quantum Dots

The stringent requirements of space applications for infrared detector arrays include high quantum efficiency, extremely low noise, ambient (radioactively cooled) operation, radiation hardness, etc. Dr. Sarath Gunapala (JPL) presented the state of the art of semiconducting quantum dots (QDs) as promising optoelectronic devices. Because the nanoscale carrier confinement is in all three dimensions (d ~20–60 nm), QDs have discrete energy levels with sharp delta-function type electron state densities, large optical nonlinearity, lower dark current (as a result of weak electron-phonon coupling), and a high radiation tolerance. Unlike quantum well infrared photoconductors, QD infrared photodetectors (QDIPs) work under normally incident radiation at near-infrared (< 5 µm) wavelengths. Work at JPL in the development of site- and size-controlled semiconductor QDs relied on molecular beam epitaxial (MBE) growth on GaAs substrates for suitable demonstration sensors. Although fabrication methods using self-organization (e.g., Stranski-Krastanov growth) are widely studied, site and size control of multilayered QD material has not been successful to date. Dr. Gunapala presented the latest results of QDIP grown by Stranski-Krastanov techniques. Operating at temperatures of 150 K, QDIPs have shown sensitivity that is a factor of 10 higher than other non-cooled sensors (e.g., silicon microbolometers). In addition, QDIPs have very high carrier lifetimes. In the past several years, high-density In(As)Sb QDs on InP substrates have performed as distributed feedback lasers at 1.3 µm. With an area density of 4×10^{10} cm^{-2}, the In(As)Sb QDs at room temperature emit luminescence at a wavelength of 1.7–2.3 µm. QD lasers operating at 2 µm in continuous wave mode (CW) were demonstrated. Narrow-ridge waveguide lasers lased at up to 25°C in CW operations.

Single-Electron Transistors (SETs)

Dr. Carl Stahle presented developments at NASA Goddard Space Flight Center (GSFC) in SET technologies. The SET can be used as a very low-noise, fast, muliplexable, readout amplifier integrated with cryogenic detectors to produce ultra-sensitive, large format detector arrays for high-priority NASA missions in the far-infrared and sub-millimeter ranges. Single-electron transistors are quantum-effect devices that use the quantization of charge on nanoscale islands and function as ultra-high-performance electrometers [6]. The nanometer scale of the tunnel junction between the small metallic “island” and the source and drain is essential to the charge quantization of the SET. If the capacitance across the tunnel junctions is small enough, the current flow is blocked by charging effects and regulated by a potential applied to the capacitive gate. The response of source–drain current to gate charge is periodic, with a period equal to one electron’s gate charge. The GSFC SETs operate at below 1 K with a sub-femtofarad input capacitance and dissipate only picowatts of power. The fabrication and circuit schematic of a radio frequency (RF) SET with its readout and multiplexing electronics is shown in Figure 3.2 [7]. A two-channel RF-SET system has been demonstrated and a fifty-channel system is under development at GSFC.

Functionalized Nanowire Surfaces for Biochemical Characterization

Dr. Brian Hunt (JPL) described a study of semiconducting nanowire sensors based on the change in conductance as the wire’s surface adsorbs molecules. The device acts as a chemically sensitive field-effect transistor in which the conductance change arises from the electrostatic gating or charge transfer from the attached molecule. The study has demonstrated detection limits in the picomolar to femtomolar range for a few model molecular systems [8]. Nanowire molecular sensors operate at sub-nanowatt power levels and can be made chemically specific with functionalized wire surfaces.

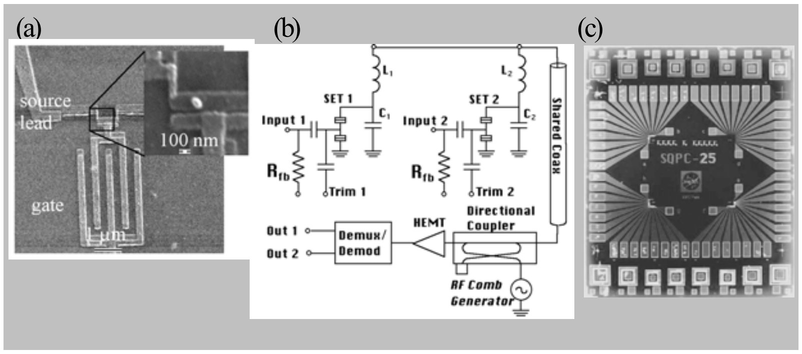

Figure 3.2. (A) Scanning electron micrograph of an SET with 0.5 fF input gate fabricated at GSFC. Inset shows 60 nm × 60 nm tunnel junctions connecting source and drain leads to an SET island. (B) Schematic of RF readout and multiplexing system. (C) Substrate for RF-SET fabrication showing 16 RF inductors located along the top and bottom of an 8 × 10 mm chip (courtesy of NASA).

Work at JPL has demonstrated nanowire chemical sensors using CNT and silicon nanowires grown by chemical vapor deposition from nanoscale catalyst particles. The CNT devices are produced using lithographically patterned molybdenum electrodes followed by the definition of an iron nanoparticle catalyst region and chemical vapor deposition growth of the nanotubes. The resulting single-walled nanotubes have electrode gaps ranging from 100 nm to 2 µm. The silicon nanowire is grown from gold nanoparticle catalysts or nm-thick gold films followed by patterning with titanium/gold electrodes. Previous sensing efforts at JPL have focused on bare, non-functionalized nanowires for both gas and liquid phase chemical sensing. The liquid phase testing has focused on testing for amino acids—a key molecule of interest in astrobiology. Conductance versus time was measured for electrically gated nanotube sensors as the concentrations of three different amino acid solutions were varied. These preliminary experiments showed clear differences in the conductance for arginine, aspartic acid, and tryptophan. Further studies are under way aiming at optimizing the sensitivity of the device. These will include adjusting the device gate voltage and understanding the pH effect. The initial round of experiments suggests that even non-functionalized nanotubes may be useful in amino acid sensing.

Nanoscale Mapping of Chemical Heterogeneity

Dr. Tinh Nguyen (NIST) described the ongoing development of techniques for providing the mapping of surfaces at nanoscale resolutions using chemically functionalized AFM probes or a chemically modified CNT. By manipulating the relative humidity (RH) of the tip-sample environment, AFM tips can image nanoscale hydrophilic and hydrophobic regions for the investigation of self-assembled monolayers and polymer blend samples. By use of thiol chemistry, CH_3 and COOH functionalized AFM tips were created. Using a NIST-patented humidity chamber, the functionalized AFM tips generated high-contrast images of hydrophilic and hydrophobic regions with RH values of > 50 percent. At high RH levels, AFM imaging could detect the minor difference in polar surface energies between different surface chemical domains.

Mechanical Resonators

Professor Nick Melosh (Stanford) presented an interesting alternative to electrochemical-based detection methods for gas- and liquid-phase analytes. As with any mechanical system, the length and stiffness of a structure implies a natural resonance frequency. For instance, 20 nm long metallic nanowires under stochastic excitation result in natural vibration frequency of 100–200 MHz, which is detectable as magnetic-field-induced voltage. The adsorption of individual molecules onto the nanowires causes a measurable change in the natural frequency. In a viscous liquid, the natural frequency will also change as molecules adsorb to the wire's surface with a resultant change in the viscous damping coefficient. For a typical protein of 8 nm in diameter, the change in viscous drag is approximately 2 percent. Experiments indicate that nanoscale mechanical resonators can detect three proteins with 99 percent confidence and have demonstrated a linear response up to the adsorption of 3,000 proteins. Such a resonant sensor is attractive for microfluidic systems and is also orthogonal to electrochemical sensing techniques.

Nano-Rheostats

Dr. John Cumings (Stanford) emphasized the emerging use of transmission electron microscopy as a powerful tool for studying the dynamic properties of nanoscale devices. TEM studies have unraveled important and subtle effects in device operation such as structural changes, chemical sensitivities, electromagnetic fields, and heat flow. Dr. Cumings' work focused on a novel *in situ* nanomanipulation probe for handling MWCNTs. TEM imaging demonstrated the telescopic extension of MWCNT using the *in situ* probe. Experiments have determined the friction forces between nanotube surfaces and the variation in nanotube electrical resistance with extension. These experiments indicate that the MWCNT can potentially serve as a nanoscale rheostat.

Nanofluidic, Size-Exclusion Chromatography

The search for life on other planets will require extremely miniature, low-power instruments capable of detecting microbial forms in unknown states (e.g., extant, dormant, extinct, or fossilized) and of unknown chemical composition and concentrations. Dr. Sabrina Feldman (NASA ARC), working with engineers and scientists from JPL, is developing a nanofluidic lab-on-a-chip based upon the principles of size-exclusion chromatography (SEC). This technology may be used to elucidate the geochemical and biological history of soil, ice, and water samples through the identification and quantification of polar and nonpolar macromolecular compounds. The molecular separation in SEC is based on the characteristic elution times of molecules traveling through microchannels that contain thousands of nanoscale features. SEC is a standard technique on Earth for studying humus, oils, bitumen, and other organic substances in soil and sediment samples. The conventional SEC column is packed with silica or polymer beads with dimensions of 10 µm and average pore sizes of 10–1000 nm. Organic macromolecule separation using SEC requires only that molecules differ in diameter and avoids the second-guessing with regard to missing classes of organic molecules.

Nanopore Gating of Single Molecules

Professor Holger Schmidt (University of California, Santa Cruz) discussed a new approach to fabricating integrated optical sensors for ultra-small liquid or gaseous sample volumes. Hollow-core antiresonant reflecting optical waveguides [9] and nanopores are combined to achieve single-molecule sensitivity and selectivity. Using a focused ion beam, individual nanopores are etched with diameters of < 60 nm. Such nanoscale pores act as gates for selective introduction of individual molecules into fluidic waveguides for the study of optical properties and resonant photonic states. Changes in the ionic current blockade as molecules pass through pore openings allow one to electrically distinguish individual biomolecules. By combining these nanopores with integrated optics, the optical properties of molecules can be simultaneously studied using standard spectroscopic techniques (e.g., fluorescence or molecule-specific Raman scattering). The current research seeks to integrate the gating and sensing technology in a lab-on-a-chip design.

Electrophoretic Nanofabrication

Benjamin Sullivan outlined ongoing research with Dr. Michael Heller (University of California, San Diego) on the development of microelectronics arrays for the electrophoretic and dielectrophoretic control and assembly of nanoscale components. As discussed earlier in this report, the manufacturing of homogeneous and precisely functionalized nanocomponents is both difficult and expensive. While self-assembly at the nanoscale is possible under certain limited conditions (based on biological models), trying to use self-assembly alone to create viable higher-order integrated devices may be a somewhat naive approach.

Developed for genomic research and DNA diagnostic applications, CMOS (complementary metal oxide semiconductor) microarray devices generate configurable electric field geometries for the surface transport of charged reagents and analytes. Experiments of electric field assisted self-assembly illustrate the potential for nanoscale fabrication using this approach. The success of electric field directed self-assembly at the nanoscale depends on the development of stable, homogeneous micro- and nanoelectrode array platforms that can carry out highly parallel assembly of components. Other methods do not provide as precise a control of nanoscale structures. In addition, electrophoretic and dielectrophoretic methods can control how functional groups (e.g., chemical ligands, proteins, DNA) are arranged around core nanostructures.

MAJOR CHALLENGES

Barriers and Solutions

Research and development at the nanoscale faces many of the same problems addressed at the microscale regarding materials, structures, and processes. Materials include thin films and novel compounds and properties. Structures are not only the layering of materials, but also the 3-dimensional shape of nanocomponents and their interaction properties. Processes are the means by which materials and structures are handled in the construction of functional devices. The understanding of the physics at the nanometer scale is still progressing. This suggests that nanotechnology’s full potential will be realized only when such novel phenomena (that occur at the nanoscale) have been established and understood.

The methodology of nanoscale sensors faces several challenges in meeting the visions outlined above. Due to an extensive overlap between sensor technology and nanomaterials, some of the challenges mentioned here have already been discussed at length in Chapter 2 of this report. The reader is therefore advised to turn there for more detailed coverage on certain issues.

Production and Refinement

The production of nanomaterials such as carbon, metal, and oxide nanotubes is limited. Refinement and purification techniques are needed to select chemical, electrical, and mechanical subgroups of species produced in bulk volumes.

Manipulation and Control

Nanoscale materials require nanoscale handling techniques; yet these techniques must be driven at macroscale dimensions.

Lithography

Reliable nanoscale deposition tools (e.g., inks, masks, or nanoindentations) need to be developed.

Nano-Micro-Macro Integration

Bridging the gap between the macroscale and nanoscale worlds requires standardized interfaces and novel tools. Wireless communication may be applicable along with networked communication infrastructures.

Toxicology

Nanoscale materials must be safely produced, stored, handled, and recycled. Standardized practices are needed to protect the community and the environment.

Robust and Reliable Architectures

The inherent anomalies of nanoscale fabrication may require greatly improved fault-tolerant designs. Radiation hardness may come from nanoscale systems' inherent multiplicity of capabilities.

Self-Calibrating Networks

Large sensor networks must be self-calibrating. Networking technologies must be efficient and employ error-correcting capabilities.

Data Fusion

Heavily networked sensor systems may generate data fusion problems similar to the problems faced by massive data warehouses. Solutions may be found outside of typical aerospace disciplines.

GOALS

5–10 Years

Continued Demonstration of Mission-Enabling Solutions Employing Nanotechnology

- New materials
  - band-gap engineered semiconductors
  - electron-phonon decoupling
  - radiation shielding improvements
- Improved passive components
  - fatigue-resistant wiring
  - high-density capacitors
- Improvement in device performance
  - sensitivity, selectivity, weight, power, volume

Development of Novel Approaches

- Fault-tolerant architectures
  - reduced sensitivity to radiation
  - enhanced durability and reliability
  - monitoring and predicting failures
- Distributed sensor networks
  - “lick and stick” technology
  - improved integration and coverage
  - feedback control and monitoring
- Sensor self-calibration

Control of the Fabrication Process

- Necessary tools still under development
  - fluidic self-assembly
  - template pattern control
  - electrostatic assisted assembly

Beyond 10 Years

Leveraging the Nano-Bio-Info Convergence

- Habitat and well-being monitors for astronauts
- Search for and characterization of life on other worlds

Development of Biomimetic Systems with Repair and Regulation Capabilities

- Complex natural mechanisms for locomotion and the efficient conversion and storage of energy

CONCLUSIONS

Nanotechnology holds great promise in the development of novel sensors and instrument components to build devices for future space missions. The goal is to demonstrate solutions that employ the novel properties of nanoscale materials. Pushing toward smaller feature sizes will also necessitate innovation for integration between the nanoscale and the microscale. This issue will be discussed in detail in Chapter 6 (Nano-Micro-Macro Integration and Nanomanufacturing).

Clearly, any new technology faces obstacles within the risk-averse aerospace community. The high cost of missions dictates the use of reliable and flight-proven hardware. Under these conditions, the incorporation of new technology is always a challenge. Program managers must carefully weigh the risks against the benefits of newly developed technical solutions. To incorporate novel solutions successfully to the satisfaction of the end user, managers are best advised to partner with nanotechnology experts and system engineers. The risks for novel sensors employing innovations in nanoscale engineering are offset by the potential for improvements in the areas of reliability, sensitivity, and selectivity, along with savings in mass, power, and volume. In addition, the need to understand the underlying mechanisms of cellular operations will also drive the development of nanoscale technology. As discussed earlier in this report, scientists and engineers are making strides to mimic the designs of biological systems. Indeed, life itself is an existence proof of nanoscale possibilities while remaining an enigmatic engine of mystery.

As future NASA missions attempt to identify the signs of life on the surface of Mars and the moons of Jupiter, nanoscale devices are expected to play a key role in analyzing the nature of any complex molecules uncovered. On Earth, developments in genetic testing have reshaped our understanding of nature's tree of life. Should life exist elsewhere in the solar system, the thrust to understand the origins and functions of extraterrestrial samples may provide the largest impetus for developments in space-based nanoscale devices.

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4. MICROCRAFT

Breakout Session Co-Chairs: Brian Wilcox and Tim Fischer

VISION

A vision for microcraft is that nanotechnology will enable new vehicle design, construction, and operation concepts that will not only dramatically reduce unit costs but also expand capabilities in ways that are inconceivable using conventional vehicle designs. One application could be to form "constellations" of vehicles distributed throughout an environment for gathering data sufficient to characterize all spatial and temporal variations of the phenomena under study. For example, imagine trying to monitor the Earth's weather with a single weather balloon floating around the globe. It would be impossible to know if changes in the instrument readings represented variations in space, time, or any combination of the two. However, many weather stations distributed throughout the atmosphere densely enough to provide highly correlated readings of adjacent stations would provide a more correct data set, and hence would provide the basis for constructing an accurate model. In other words, by ensuring a dense enough sampling array that adjacent readings (both in space and in time) are always very similar, it is highly unlikely that small but important local phenomena would "slip through" a sensor net undetected. This ubiquitous sensing allows for a level of environmental modeling, prediction, and validation that is completely unaffordable with macroscale vehicles.

In addition to resolving the space-time ambiguity of dynamic environments, constellations of microcraft can provide multi-aperture remote sensing as well as improved survivability and robustness by tolerating individual failures. Furthermore, such an ensemble of microcraft could ultimately allow for useful phased array sensing or transmission over huge equivalent apertures (i.e., when the distance between vehicles is comparable to the wavelength).

STATE OF THE ART

The current state of the art in microcraft development can be summarized as follows: operational spacecraft have been flown in the ~1 kg range, the Sojourner rover explored parts of Mars with a mass of ~10 kg, and commercial communication satellites are available (e.g., Orbcom) at a mass of < 100 kg. These systems have fully functional power, communications, thermal control, and mobility systems. Microcraft recently deployed and used effectively by DOD include the "Dragon Eye" (~2 kg), a hand-launched unmanned aerial vehicle (UAV) that returns images from "over the next hill," as well as the "Pacbot" (~20 kg) unmanned ground vehicle (UGV) for exploring caves and tunnels and examining suspected explosives, and the "REMUS" (~40 kg) unmanned underwater vehicle (UUV) for mine-hunting. The research community has prototypes of UAVs and UGVs as small as 10–100 grams. No currently operational microcraft rely on nanotechnology for their basic operation.

MAJOR CHALLENGES

Barriers and Solutions

One of the major challenges faced by microcraft developers is to provide adequate power and energy for such small vehicles. For vehicles that must move through a turbulent fluid such as air or water, the drag is proportional to the surface area, but the stored energy is proportional to the volume of the vehicle. This means that the endurance of the vehicle (operational lifetime without refueling) is roughly proportional to the vehicle's length. Reducing the size from meter to centimeter scale will reduce the endurance by a factor of a hundred. In practice, the problem is much worse than this, since small batteries or power plants currently have much lower "specific power" than larger units. Their energy or power levels drop much faster than their mass, so the energy per unit mass or the power per unit mass is very poor compared to available large components. This problem will be directly addressed by nanotechnology, since packaging overhead and other current practical (but not theoretical) limitations of these small components can be overcome.

A solution to the fundamental energy-scaling problem is to harvest energy from the environment. For example, solar power has the property that the power received by the vehicle is proportional to the surface area, and hence stays proportional to the fluid drag power required (at any scale). Solar powered ground vehicles (where rolling resistance is proportional to mass) actually have increased performance when they are made smaller. Other environmental energy sources that can be harvested are any local disequilibrium in temperature or chemical composition or shear in or between fluids. An alternative solution to the power problem is to use alpha-voltaic power. Here, electricity is created by a small bit of radioisotope that emits alpha particles using semiconductors similar to solar cells. With nanotechnology, there is a reasonable prospect of creating alpha-voltaic power cells that are not quickly degraded by radiation damage. Ten-year lifetimes are plausible (as compared to months with current technology) while having specific energies orders of magnitude greater than any chemical energy storage system. Nanotechnology also offers a reasonable prospect of increasing the specific energy of chemical batteries almost 10-fold compared to the output from current batteries (~1000 joules per gram), e.g., approaching that of chemical fuel consumed by large engines.

To make effective use of microcraft, there is a need to transition the present mission operations paradigm of many humans per vehicle to many vehicles per human. This is only possible by increasing the computational power on each vehicle. The cost of computation in terms of mass and power is a small burden on current large vehicles but is a disproportionate burden on very small vehicles. As Moore's law continues to drive commercial electronics further into the nanotechnology regime, we can expect that the amount of energy per stored bit will continue toward the theoretical limit at the rate of about one order of magnitude every 5 years. Assuming the volume of each bit declines at the same rate, one can expect that microcraft will be miniaturized in mass and power at roughly the same rate as Moore's law. Thus, one can expect simultaneous performance increases and mass reductions of about a factor of 3 every 5 years. In 10 years, an order of magnitude improvement in both mass and performance can be expected. This means that the mass fraction of the computer can go from ~3 percent of a 100 kg vehicle to ~30 percent of a 1 kg vehicle in 10 years while having a ~10-fold increase in performance.

Communication is another major challenge area for microcraft. While it is true that large vehicles can gather data much faster than they typically can transmit data, this effect becomes much more pronounced for microcraft. Imaging sensors and transmitting antennas both have limiting data rates proportional to their aperture area (other things being equal). However, if the power budget drops proportionately with volume, then the data transmitted per unit data gathered drops with the cube of the dimension. This can be addressed by communicating at higher frequencies, which may be enabled by nanotechnology, or by having dense networks of microcraft that only need to communicate short distances between each other to get information back to a central relay point.

Another major issue for microcraft is thermal control. It is nearly impossible to maintain the interior of a very small vehicle at a constant temperature and different from the ambient value because of a large surface-to-volume ratio. This in turn leads to very short thermal transport distances, as well as little volume available for insulation. If one tries to insulate the interior against the cold when not operating, then rejecting the waste heat becomes difficult when the vehicle operates. Nanotechnology can make great contributions by providing new materials that have much higher or lower thermal conductivity and by enabling the development of light, reliable, and accurately controllable switches and radiators for thermal control. Nanotechnology can ultimately provide components that work over very large temperature ranges so that thermal control is not needed beyond sustained good coupling to the environment.

Table 4.1
Microcraft & Constellations

GOALS	**HARD PROBLEMS**
• Reduce mass of spacecraft by factors of ~100 in 10 years and ~1000 in 20 years, while increasing on-board computational performance by ~100X, at same cost per kilogram • Fly “constellations” of 100–1000 microcraft for dense spatial and temporal sampling of phenomena	• Exploiting nanotechnology for ≥ 10X breakthroughs over current state of the art • Performance/mass ratio for energy storage and conversion, communications (at higher frequencies), thermal control (better conductors, insulators, and components that work in extremes), actuators and thrusters, and on-board computing so 1 human manages 1000 spacecraft
VALUE TO SPACE SYSTEMS	**STATE OF THE ART**
• Distributed robust remote sensing • Simultaneous dense sampling of phenomena for accurate modeling of Earth, planetary, and space environments (vs. understanding weather via a single weather balloon floating around the Earth!)	• Commercial satellites (e.g., Orbcom) @ 40 kg • Sojourner Mars Rover @ 11.5 kg • “Picosats” (some MEMS) 0.27–1 kg on expendable and STS vehicles • Variety of lab prototype vehicles at 10–100 g • All with sensing, computation, communications, and actuation

A final major challenge area for microcraft is in the area of mobility actuators and sensors. As with power components mentioned previously, the specific performance of current actuators and thrusters drops precipitously for highly miniaturized components. Again, this is due to packaging overhead and surface-to-volume effects that nanotechnology may overcome (e.g., by creating nanoporous materials with vast surface area packed in a small volume). Nanostructured materials may provide high degrees of force and deflection at high rate and low power for use in actuators. Nanoscale pyrotechnic “digital” thrusters with high specific impulse seem possible. “Gecko feet” will allow small vehicles to traverse unimpeded through jungles, collapsed buildings, etc.

Nanofabricated electric or magnetic devices may offer breakthrough performance for small motors, ion engines, and other mobility components needed for microcraft. Nanotechnology sensors for mobility may give new capabilities in inertial or position sensing.

GOALS AND CONCLUSIONS

5–10 Years

- A consensus roadmap for achieving the advances in microcraft described in this chapter requires that the first ~5 years be focused on the development of the component technologies needed to meet the technology challenges described above.
- Within 7 years it should be possible to incorporate some of the "low hanging fruit" to fly a ~1 kg spacecraft with approximately the same performance (but communicating at higher frequencies) as currently available spacecraft (~100 kg).
- In 10 years it should be possible to reduce the microcraft's weight by another order of magnitude (~100 grams), while demonstrating the flight of a small constellation (~100 units) of ~1 kg spacecraft at a total cost about equal to a single present-day ~100 kg spacecraft. This constellation not only will have 100 times the sensing and data bandwidth of the single spacecraft it replaces, but the "synergy" of the constellation will allow it to resolve space-time ambiguities that are completely beyond the reach of individual spacecraft.

Beyond 10 Years

- In 15 years it should be possible to fly a large constellation of ~1000 spacecraft, each with a mass of ~100 grams. In 20 years time, the computational power per microcraft can be improved by 2 orders of magnitude over present vehicles, even as the mass of the computer has been reduced also by 2 orders of magnitude. This means that the ~100 gram vehicle incorporating 30 grams of computing will have 100 times the performance of today's best laptop computers. This will allow the constellation of 1000 microcraft to be controlled by a small human team (perhaps only one person), since the combined processing and data reduction will be that of 100,000 present-day computers. Similar roadmaps apply to UAVs, UGVs, UUVs, etc., with roughly the same masses and constellation sizes along the same timelines.

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5. MICRO/NANO-ROBOTICS

Breakout Session Co-Chairs: Metin Sitti and Jim Von Ehr

VISION

Intelligent and autonomous robots have been envisioned since Karl Capek coined the term robot. Nanotechnology will provide new capabilities for building robots, including better materials, improved power sources with increased power density, advanced computers, and better sensors. Smaller robots will be manufactured at lower cost than larger ones, providing the opportunity of deploying large collectives of small robots to solve tasks in new ways. Specific to space applications, micro/nano-robots could enable in-space (Crew Exploration Vehicle, space station, Hubble telescope, and satellite) and planetary inspection, maintenance, and repair. Mobile micro/nano-robots would search for life on planets, retrieve samples, and perform analysis on board. Miniature devices inside the body could monitor the astronaut's health during a space mission. Finally, in-space assembly and construction with massively parallel micro/nano-robots and miniature manufacturing robot workstations for unanticipated needs would become possible.

Micro/nano-robots could be applied to a wide range of potential areas. Health care in general would greatly benefit from using miniature medical micro/nano-robots, in particular areas such as diagnosis, drug delivery, and surgery inside the human body. This capability would have significant impact on medicine. Environmental monitoring for detecting toxic materials, chemicals, pathogens, nuclear materials, etc., could be made possible by mobile (flying, climbing, swimming, walking on water, walking, etc.) miniature micro/nano-robots. Such robots could also be used for surveillance for security purposes and for search and rescue in disasters. Furthermore, mobile self-reconfigurable miniature robots could enable novel, robust, flexible, and versatile displays, sensor suits, construction, and manufacturing systems. Large-scale robots with micro/nano-grippers could be used as scientific tools to precisely characterize frictional, mechanical, adhesion, and biochemical properties of nanoscale materials and to prototype novel electronic, optical, and biochemical nanodevices. Massively parallel nanomachines would enable high-density data storage, micro/nanomanufacturing, and micro/nanoassembly systems.

MOTIVATION AND DEFINITION

Macroscale robots are built for repetitive or meticulous manufacturing, dealing with hazards, operating remotely, or monitoring things that happen too fast, too slow, or too infrequently for humans to pay attention to. Such robots are scaled to the size of the task domain and typically powered by wall current or large batteries. Smaller robots made with better components can be less expensive, more ubiquitous, and, if well programmed, collectively more versatile than their larger cousins.

A consensus on nomenclature for describing small robots is hard to reach at present. Some people categorize devices by overall size, some by the dimensions of the smallest parts, and others by the scale at which the robot operates. For this report, the size definition is as follows: Meso-robots are those with overall sizes of 100 mm, milli-robots have overall sizes of up to 10 mm, microrobots have overall sizes of less than 1 mm, and nano-robots are those with overall sizes of less than 0.1 mm. The sizes of the parts would vary with these scales, but it does not seem appropriate to call a 100 mm box a nano-robot simply because it has some nanoscale components. Micro- and nano-robots obviously require new ways of powering themselves, new actuation mechanisms, and new control techniques. Nanotechnology provides new tools to solve those problems, and nano-robotics can assist in the development of nanotechnology by allowing for reaching into and interacting with the nanoworld in a controllable manner.

Robotics can be broadly divided into tethered devices and autonomous devices. Tethered devices do manipulation and fabrication under the control of an external computer, taking as much power as they need from the electrical grid, with components ranging from macroscale to nanoscale. Autonomous devices must carry their power, actuation, computation, sensing, and communication with them. That feat is commonplace for biological entities like bacteria but has not been demonstrated in microscale man-made devices. There are many difficult challenges, and huge commercial opportunities, in developing each of those technologies (power, actuation, etc.) individually. Pulling them all together into a package that can be called a nano-robot and coordinating large numbers of them to work together is still beyond the state of the art. However, such devices could have immense utility in health care, surveillance, and space-based manufacturing.

Researchers from the United States once led the world in tethered macroscale robotics for manufacturing, but leadership has clearly transitioned to Japan. American companies like iRobot®, government labs such as Sandia National Laboratory, and academic institutions such as Carnegie Mellon University are arguably in the lead today with autonomous robots, but the United States should not become complacent. It is vital that breakthroughs are quickly transitioned from the research lab to the marketplace, so that the economic value created by research may be captured and fed back into the next generation of innovation. Basic characteristics of micro/nano-robots can be summarized as follows:

- Operation involves new physics and mechanisms.
- Smaller, faster, lighter, and cheaper than current robots.
- Provide direct access to smaller spaces and scales.
- Deployable in large numbers and can be distributed widely.
- Require multi-length-scale system integration in case of interaction with human-scale objects (macro/micro/nano/molecular).
- Can be inspired from or integrated with biological systems at the micro/nanoscale to develop engineered bio-nano systems.
- Interdisciplinary research is essential for their design, building, and control.

STATE OF THE ART

Current micro/nano-robotic systems can be grouped in two basic categories: miniature mobile robots with overall sizes down to a few centimeters, and tethered robotic devices that can manipulate on the nanoscale. Many groups have demonstrated centimeter-scale autonomous and mobile microrobots that can walk, fly, swim, climb, and spin. Using current-technology silicon microfabrication techniques, a walking robot with solar cells, electrostatic actuators, polysilicon and silicon carbide (SiC) hinges and joints, and CMOS-based driving, communication, and control electronics can be integrated into a 1 cm^3 walking or flying robot [1]. A miniature CMOS-based camera with a battery and wireless communication unit has been integrated into a 1 cm diameter and 2 cm length microcapsule for endoscopic screening of the digestive tract inside the human body [2]. These passive sensor capsules are commercially available. However, upgrading these passive capsules into active robotic capsules is an open challenge. Self-reconfigurable, miniature robots with sizes down to 25 cm [3] have been built to demonstrate distributed and collaborative control of approximately 10 robot units for spider, snake, wheel, etc., types of locomotion by just changing their configuration [3, 4]. Building much smaller microrobots using chemically powered moving parts is a promising direction. Using ATP or glucose, biomotors or heart muscle cells have been actuated to rotate a propeller/flagellum or walk a robot body on a surface with a periodic motion [5].

Scanning probe microscopes (SPM) became the main robotic system for manipulating atomic, molecular, and nanoscale entities in the early 1990s. Researchers used electrical pulses and/or physical contact to pick and place, or simply push, atoms or molecules on a surface in two dimensions to build structures. AFM probes are currently the most common nanomanipulators due to their ability to image and manipulate a wide range of nanomaterials while performing *in situ* force sensing during manipulation. Nanoparticles, carbon nanotubes, nanowires, nanocrystals, proteins, DNA, RNA, viruses, bacteria, cells, etc., can be pushed, pulled, cut, bent, indented, twisted, bonded, and deformed using AFM probes. Furthermore, optical tweezers, dielectrophoretic and electrophoretic manipulators, and magnetic tweezers can be used to manipulate entities, typically biological samples, due to their tiny and non-contact interaction forces. These manipulation capabilities enable novel means of prototyping nanodevices and characterizing nanomaterials. Virtual-reality-based user interfaces for these microscopes have been developed for user-friendly and intuitive nanoscale manipulation and imaging for scientists [6]. Two- and three-dimensional microassembly systems have been used to manipulate micro-parts and cells. Gene-injection manipulators and micro/nanomanipulators [7] show the many industrial applications of these precision manipulation systems. As commercial applications of SPM-based nanodevices, thousands of AFM probes called “millipedes” have been prototyped by IBM for high-density data storage applications, using a technique where nanodots are indented and erased on a polymer surface [8]. Also, arrays comprising thousands of AFM probes have been used to write lines and dots on surfaces with nanometer scale precision via dip-pen nanolithography (DPN) [9].

Useful Developments in Nanotechnology

Sufficient power is arguably the key issue for autonomous robots at any scale. Nature has shown the power and efficiency of chemical fuel cells metabolizing glucose or ATP. Some groups have built devices that can function in a similar manner; such a biological (or biomimetic) approach looks promising. Conventional fuel cells are promising if the technology significantly advances and miniaturizes. Microscale batteries are useful but must be charged somehow (e.g., with miniature solar cells), which could limit their deployment to areas with proper lighting. Research into atomically powered devices converting safe beta decay into micro-power generators is promising [10], but the public’s reaction to any technology containing the word “atomic” may preclude deployment.

Actuators are currently seen in a variety of technological applications, few of which scale gracefully to the micro- or nanoscale. Again, nature shows some functional ways of linking large numbers of low-power, low-range-of-motion devices such as muscle cells or molecular motors to achieve a wide range of motion and force. New actuators based on carbon nanotubes show promise in achieving a 10-fold improvement in power over natural muscle, but much development remains.

Nanomaterials are progressing rapidly in the macroscale world, largely due to the wide range of potential markets, and are expected to be beneficial to the microtechnology and nanotechnology worlds in a number of ways. Greatly improved strength-to-weight ratios allow small systems to support higher static or dynamic loads. Looking again to biology as an example, an abalone shell is over 3,000 times tougher than the materials comprising that shell. The increased toughness is due to clever nanostructuring [11]. As discussed at length earlier in this report (see Chapter 2), space missions will benefit greatly from mimicking such structures to produce far stronger engineering materials than current ones. Multifunctional materials will allow for merging actuation, structure, sensing, and power storage in a skeleton comparable to an insect's exoskeleton. Top-down (lithographic), bottom-up (self-assembly) nanofabrication and microassembly are advancing rapidly. Robust micro- and nanoassembly will be required to assemble the heterogeneous components of a nano-robot. Automated parallel assembly via early-generation microrobots will be required to achieve the production scale and low cost that is needed to build huge collectives of advanced micro- and nano-robots.

Nanobiotechnology has been a very popular and fruitful area of nanoscience research, particularly biomimetic research. Approaches such as integration of natural muscle with MEMS to create actuators powered by ATP and synthetic gecko-foot adhesive show that it is possible to adapt some of nature's mechanisms to synthetic systems [12].

MAJOR CHALLENGES

The overall challenge in developing nano-robotics is to balance the need for long-term fundamental research with the equally important need to deliver commercial products in order to earn a return on that investment for society. With sufficient benefits spinning out of this program, there will be adequate money for R&D, just as with the semiconductor industry. Government funding for university and government research, while necessary for basic research, will be insufficient for development and commercialization of nano-robots. Private industry funding is too focused on the short-term to make the necessary investments to advance the knowledge of the required technologies. There is a need to find a way for government, universities, and private industry to work together to advance each step of the roadmap—from basic research phenomena to functioning systems.

Three major challenges of micro/nano-robotics can be summarized as follows:

- *Miniaturization*: Scaling down requires miniature and efficient power sources or wireless power transfer methods. Micro- and nanoscale parts, sensors, actuators, controls, and tools need to be heterogeneously integrated in order to manufacture miniature robots. Integrating biological entities with non-biological systems for miniature, efficient, and robust hybrid microrobots is a further challenge. New types of miniature actuators are indispensable for moving the robot body as well as for manipulation at the end-effector sites.
- *Assembly*: Three-dimensional heterogeneous system integration at micro/nano/molecular scales has not yet been achieved. Robust approaches are needed for mechanical and electrical interconnects and for managing cumulative errors caused by assembling large numbers of components. Self-assembly is appropriate for small parts, but has not been demonstrated as a flexible and general-purpose systems-level strategy.
- *Programming and control*: Control of a large number of micro/nano-robots is a new challenge considering the complexity, communication, localization, and distributed behavior.

BARRIERS AND SOLUTIONS

A major barrier in micro/nano-robotics is the development of robot mobility such as surface climbing, walking, flying, rolling, swimming, walking on water, and hopping. Novel smart adhesives, high strength-to-weight ratio nanomaterials, miniature and high power density actuators and power sources are required for mobility. In addition, power becomes a critical barrier when scaling down microrobots. Possible solutions for this issue could be to use chemical energy as a miniature power system by integrating biological entities to non-biological robots. Another route to meet this challenge could be harvesting energy from sources such as mechanical vibrations; chemical, temperature, and flow gradients; and transferring/beaming external power optically or magnetically via microwaves.

Actuation is another major barrier for micro/nano-robots where high precision, high power density, high efficiency, lightweight, miniature, and sensor-integrated nanoactuators are required. Carbon nanotube, piezoelectric, conductive polymer, thermal, electrostatic comb-drive, and shape memory alloy micro/nanoactuators are all being explored. Furthermore, new programming models and methods are required for controlling large collections of microrobots as active computational entities. Novel biologically inspired features, distributed control, self-organized systems, and improved communication methods could solve this issue. Finally, better design and simulation tools are required for rapid prototyping and autonomous manufacturing of micro/nano-robots. For this, continuum microscale and nanoscale physics model-based nanosimulators and multi-length scale, reduced micro-/nano-physics modeling techniques are indispensable.

Teleoperated, supervised, and autonomous control of micro/nano-robots is another issue where novel control approaches specific to these robots with new physics, short time scales, and new mechanisms should be developed. Also, in order to interface micro/nano-robots with human dimensions, advanced "augmented reality"-based user interfaces for these robots are needed.

GOALS

A more detailed roadmapping exercise might provide slightly more certainty in these estimates, but as demonstrated by the semiconductor industry, roadmapping works best when driven by considerable experience in advanced manufacturing. The experience of solving actual micro- and nano-robot problems in production and deployment improves schedule estimates. Accordingly, these should be taken as speculative at this time.

5–10 Years

- New micro-power sources (miniature and high power density)
- Advanced materials with high strength-to-weight ratio, better than that of aluminum alloys
- Advanced nanofabrication techniques capable of making 3-dimensional parts with < 100 nm features
- Parallel arrays of tethered robotic micro- and nanomanipulators
- Automated assembly of parts from 100 nm to 5 mm
- Simple cooperation of teams of 10s of meso-robots
- Millimeter size self-contained robots
- Automated 3D nanomanufacturing and assembly
- Design and simulation tools for micro- and nano-robots

- Self-reconfigurable miniature robots
- Hybrid (biotic/abiotic) robots and machines
- Parallel-automated assembly of parts from 10 nm to 10 mm
- Sophisticated cooperation of teams of meso-robots
- Simple cooperation of teams of milli-robots

Beyond 10 Years

- Sub-millimeter scale mobile microrobots
- Cooperative networks of microrobots
- Atomic and molecular scale manufacturing for 3D parts
- Collaborative construction and manufacturing at the nanoscale and the molecular scale
- Sophisticated cooperation of teams of microscale robots

CONCLUSIONS

Micro/nano-robots offer unique features, advantages, and capabilities with a wide range of potential applications in space, health care, manufacturing, materials characterization, environmental monitoring, biotechnology, search-and-rescue, and entertainment. Due to new physics and mechanisms, physics at the nanoscale requires revisiting the traditional components of macroscale robotics. Furthermore, nanotechnology opens up new challenges not seen in the macroscale, such as the coordination of massive numbers of inexpensive robots. Harnessing robots that can operate at the nanoscale, or harnessing nanoscale components to improve robots, will result in tremendous benefits for humanity.

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6. NANO-MICRO-MACRO INTEGRATION AND NANOMANUFACTURING

Breakout Session Co-Chairs: Thomas George and Stephen R. Winzer

VISION

Nanotechnology, the capability to engineer materials and devices from the molecular and atomic level, allows unprecedented access to phenomena at the nanoscale. The excitement of nanotechnology has evoked a variety of visions of the future of space exploration in which small, nanotechnology-enabled autonomous systems explore the solar system and prepare the way for human exploration of the Moon and Mars. However, at the end of the day, for novel nanoscale phenomena to be exploited for human benefit, we need to go from the nanoworld and integrate into the existing systems of the macroworld. Primarily, this entails the development of macroscale systems that can effectively exploit novel nanoscale properties without significant loss. A comprehensive set of tools needs to be generated for the fabrication, assembly, testing, and characterization of these systems. Also, the system developers should inculcate a fault-tolerant design approach, realizing that defects are intrinsic to nanoscale structures. Finally, the overall system should meet the stringent standards of space reliability assurance by not only being inherently robust during exposure to a variety of adverse space environments, but also not causing the catastrophic failure of other associated systems. Several such nanotechnology-enabled systems are envisioned to be flying on spacecraft by 2014.

STATE OF THE ART

The current state of the art in nanotechnology research is reflected in the literally thousands of publications over the last several years, including peer reviewed journal articles, conference presentations, and issued patents. The overwhelming majority of these publications discuss concepts or demonstrations of material and device properties at the nano- and microscales. Few address nano-micro integration and fewer still the development of nanotechnology-based systems or subsystems. Issues related to the development of robust manufacturing processes, including attendant standards and specifications, have largely not been considered yet.

The few examples of nano-micro-macro integration approaches provided in this section are based on technical presentations made during the NNI workshop. The first example relates to the use of carbon nanotubes as nanomechanical resonators for RF filtering [1]. The expectation for nanomechanical resonators made from arrays of nanotubes is that their intrinsically high quality will ultimately enable low-power, small-size RF transceivers because of a simpler architecture and will result in drastic reductions in overall parts counts. The nano-micro interface in Figure 6.1 is the combination of lithographically patterned conductors interfacing with single nanotubes as well as arrays of nanotubes. However, this project is at a very early stage of proof-of-principle demonstration, and a significant amount of work remains to be done in order to realize nanotube-based RF systems. Nanotubes have been proposed for many other uses, including functionalized molecular sensors, as well as many other applications in electronics, sensors, and structures [2]. The development and uses of carbon nanotubes in applied systems is a hugely active area of research and development in the field of nanotechnology (see Chapter 2).

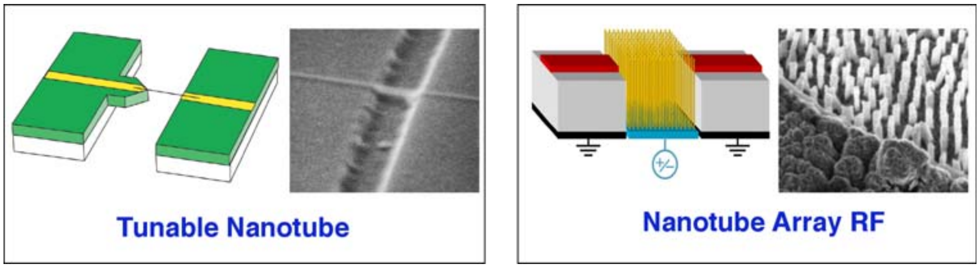

Figure 6.1. Tunable nanotube resonator (left) and a nanotube array RF filter (right) (courtesy of NASA).

In another effort, illustrating the need for understanding various interfaces at the nanoscale, Sandia National Laboratories has developed a novel biocavity laser for the detection of diseased cells [3]. As demonstrated in Figure 6.2, the nanoscale interfaces exist between the organic nanostructures and the inorganic semiconductor substrate. This is a very active area of research, challenging researchers to produce stable interfaces between two different materials by using self-assembled monolayers of compounds with both hydrophobic and hydrophilic parts.

The gas-sensing devices shown in Figure 6.3 are examples of a nanotechnology-enabled macroscopic system in which all of the nano-micro-macro interfaces have been addressed. As illustrated in Figure 6.3 (left side), the gas-sensing elements comprise thin-film resistors of nanocrystalline titania or tin oxide of thicknesses on the order of 10–100 nm. The device sensitivity varies with the thickness of the film. The micro-interfaces are lithographically patterned platinum conductors on a glass substrate. The entire device is mounted within a ceramic package in order to interface with the outside world. This device represents a strong example of a nanosystem achieving a high level of technological maturity, having been implemented in several NASA applications. As pointed out by Hunt et al. [1], the most important criteria for a good sensor are the performance (detection limit, reproducibility) and how well the sensor design is tailored to the application in question. The second example in Figure 6.3 (right side) demonstrates the use of carbon nanotubes as a sensing element. The CNTs are deposited on an interdigitated finger electrode, thus forming an integrated system comprising a humidity sensor and signal-processing unit. Developed at NASA Ames, this system is packaged suitable for flight in a U.S. Navy Delta rocket mid-payload system.

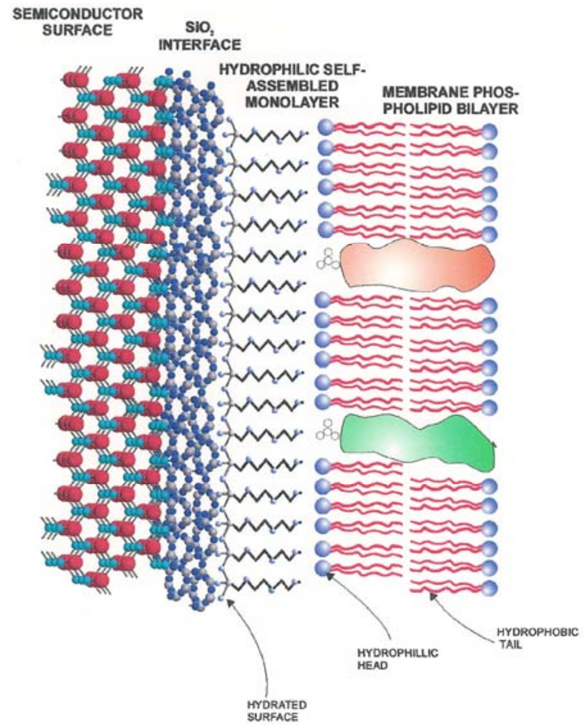

Figure 6.2. Schematic of the interface between semiconductor and SiO_2 layers, and the self-assembled hydrophilic and membrane phospholipid layers for a biocavity laser (courtesy of P. Gourley, Sandia National Laboratory) [3].

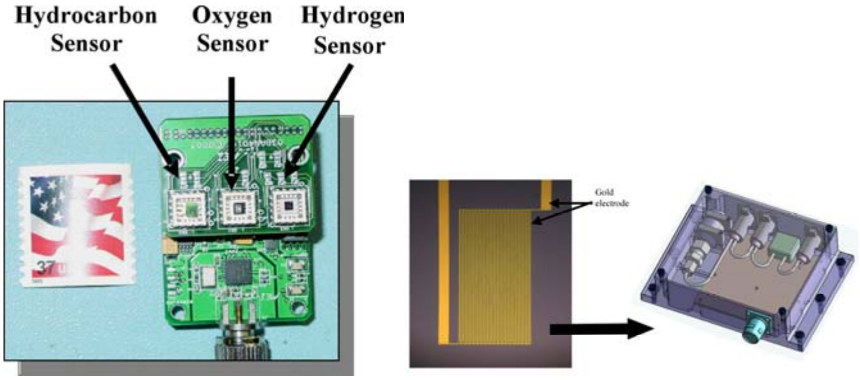

Figure 6.3. Combined hydrocarbon, oxygen, and hydrogen sensor (left); carbon nanotube-based chemical sensor system (right) (courtesy of Meyya Meyyappan, NASA Ames Research Center) [4].

These four examples are a small subset of the great many devices that show promise for aerospace applications. However, they also illustrate the powerful point that very few of these concepts and devices have reached the level of maturity to be even considered for implementation in space flight applications. Also, these devices tend to rely on the more mature MEMS and microelectronics technology for the micro-macro interfaces.

There is an equally urgent need for standards that allow for reproducible measurements of dimensions and mechanisms by which these measurements can be transferred among various processes used to manufacture nanodevices. In an ongoing effort at NIST, one approach being explored is to base the measurements on lattice constants that are known very accurately at the atomic scale for numerous crystalline materials. NIST has used single crystal silicon as such a standard for measuring step heights and line widths (Fig. 6.4). The step heights measured on the (111) plane of silicon by atomic force microscopy (AFM) and electron-diffraction result in a recommended value of 312 ±12 pm. Test patterns are also being developed in a somewhat similar manner for optics applications. These patterns are first written using a scanning tunneling microscope (STM) in a vacuum, followed by reactive ion etching to enhance the feature height (Fig. 6.5).

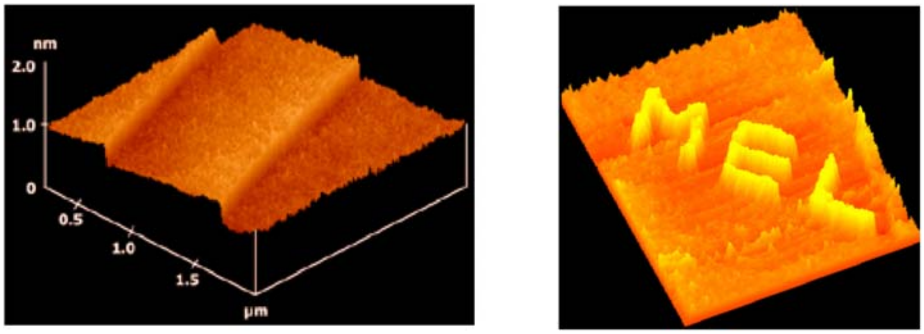

Figure 6.4. Measured step heights in Si (left) and line-width measurement and control in Si (right), after Ted Varburger and Richard Silver, NIST (courtesy of NIST) [5].

Other methods that are being used for dimensional standards include the use of molecular lattice constants and optical approaches to lay down parallel lines with tightly controlled dimensions over

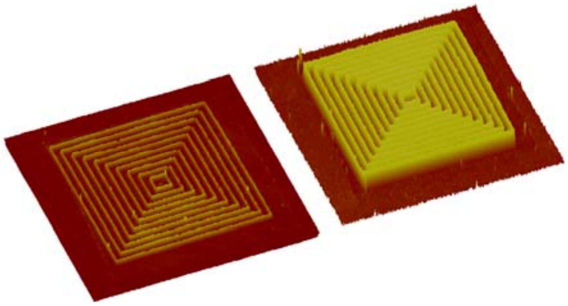

Figure 6.5. Test patterns in silicon: image taken after writing the pattern using an STM (left); image of the pattern as it appears after reactive ion etching (right). The height of the features is about 10 nm (courtesy of NASA).

the micro- and macroscale. The process for the measurement of nanoscale forces must also be standardized. These measurements are needed to set device parameters, materials requirements, structural sizing at the micro- and nanoscale, tribology of moving interfaces, and the like. They are essential elements in vetting models used for designing nanoscale and microscale devices. Jon Pratt at NIST has developed an instrument that generates a standard micro-force accurate to within 10 µN. Finally, it is likely that specialized instruments need to be built at the microscale in order to retrieve required data on materials at the nanoscale. An example is the micromachine developed by de Boer and coworkers designed to perform tribological measurements at the micro- and nanoscales (Fig. 6.6).

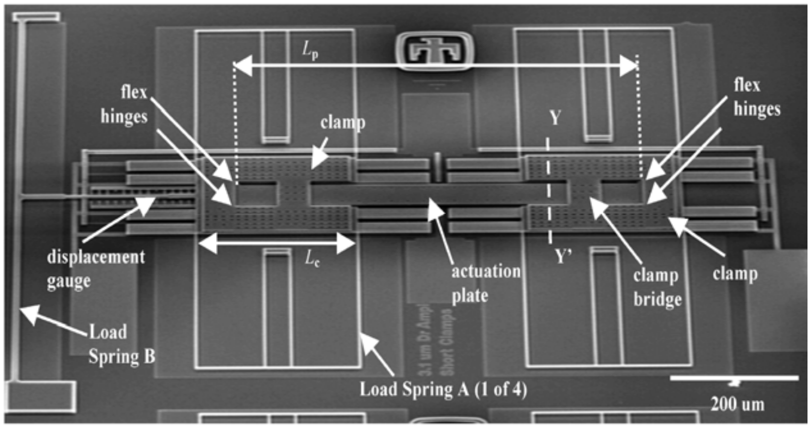

Figure 6.6. A micromachine used for tribological studies of material interfaces developed at Sandia National Laboratories (courtesy of NASA).

Tribology is a key subject area where a fundamental understanding of the forces and wear regimes of nano- and microscale devices will be explored. In the past, certain types of MEMS devices have experienced early failure due to excessive wear, which has in turn stimulated redesign of components to minimize sliding interfaces. Tribology is a difficult subject even at the macroscale and is therefore an area in demand for focused research to understand the nano- and microdevice regimes where continuum physics models may not apply.

MAJOR CHALLENGES

Barriers and Solutions

A number of scientific and engineering challenges must be overcome in order to realize the grand vision for nano-micro-macro integration. The “rubber hits the road” for nanotechnology at the end-user stage. The folklore is that the customer does not really care what is inside the “black box” as long as the ultimate system meets or exceeds the requirements for form, fit, function, and compatibility within the system-of-systems application. Therefore, given the exciting potential of nanotechnology as evidenced by numerous demonstrations of novel phenomena at the nanoscale, the question remains as to how to effectively integrate nanoscale phenomena into existing macroscopic systems. It is strongly recommended that a considerable amount of future investment be directed to system-level development of nanoscale materials and devices to develop what will be referred to here as nanotechnology-enabled systems. Such system-level development includes the following considerations.

Nano-Micro-Macro Interfaces

The key to the realization of nanotechnology-enabled systems lies in understanding and manipulating the interfaces between the nano-, micro- and macroscale for both materials and devices. From an engineering standpoint, the primary emphasis should be on minimizing capability loss, whether by novel signal transduction methods at the nanoscale or by significant improvements in materials properties enabled by nanostructures. This effort can certainly leverage the several decades of work done on optimizing the interfaces between the micro- and macroscale, most notably in MEMS and microstructure engineering for new materials systems. Thus, the investment should focus, as a higher priority, on the development of optimum interfaces between the nano- and microscales. Future investment should be directed to developing an in-depth understanding of the mechanical, thermal, fluidic, electrical, magnetic, and photonic interfaces between the nano- and microscales. For instance, reproducible detection of femtowatt energy levels and attonewton forces across nano-micro interfaces still represents a significant challenge. Also, communicating with and extracting information from a nanodevice at the macroscale requires new approaches to signal conditioning and processing, software, and power. Similarly, there remain challenges of translating the superb mechanical properties (strength-to-weight ratio) of nanomaterials (e.g., carbon nanotubes) through a macroscopic matrix. Understanding the losses that occur at the interfaces and developing the capability to deal with them require new tools and models.

Simulation Tools

System-level development of nanoscale devices and materials is a complex and challenging task that requires a significant amount of investment, as much as several orders of magnitude more than what was needed to support the basic research into demonstrating novel nanoscale phenomena. Therefore, it is imperative that a “smart” approach to nano-micro-macro integration be pursued. A crucial risk-mitigation step is the development of reliable, advanced simulation tools capable of bridging the nano-micro-macro worlds. Inherent in the development of these simulation tools is the concept of fault tolerance. This is primarily due to the fact that even though individual elements of nanotubes (carbon or others) are relatively defect-free, the presence of huge quantities of such elements patterned in a device invites “defects.” Therefore, it is extremely important to “design in” fault-tolerant approaches when developing nanomaterials and nanodevices. A significant benefit of the predictive capability made possible by these simulation tools is the early determination of the right integration approach, thus preventing the waste of time and resources in pursuing evolutionary dead-ends.

Characterization Tools

There is a dearth of standardized instrumentation required for the complete characterization of the various nanoscale properties of interest (as listed above) and more importantly, the behavior of the nano-micro interfaces. Morphological characterization at nanometer and micrometer scales is perhaps the one area in which tools such as scanning probe microscopy and electron microscopy have achieved a high degree of sophistication. Given the diverse set of properties of interest for the nanomaterial and nanodevice developers, there is a great need for additional characterization tools. These characterization tools will provide the experimental validation necessary for rapid, iterative development of nanotechnology-enabled systems.

The prospect of developing useable devices enabled at the nanoscale requires new tools to measure properties more or less taken for granted at the macro- and microscales. These include accurate measurement of dimensions and forces at the nanoscale. There are many ongoing efforts in this area at NIST, the U.S. Government lead agency for the development of standards. In addition, development of characterization tools is being pursued in national laboratories, especially the DOE research laboratories, and at universities around the country. There is a reason to expect that major industrial players will devote resources into research and development of metrology and process control tools for their production lines. However, much of this effort is likely to remain proprietary for competitive reasons.

System-Level Manufacturing (Design, Fabrication, Assembly, and Testing)

Ultimately, nanotechnology has to lead to macroscopic systems that can be manufactured and conformed to specifications pertinent to the end-application. Fabrication of devices that use nanomaterials and nanostructures also requires the development of equipment capable of reproducing these structures within the tolerance limits required for proper device functioning. It is likely that an optimum manufacturing approach may include a combination of top-down and bottom-up processes. For example, patterned nanotube arrays used for a tunable RF sensor are grown within a micromachined and patterned aluminum substrate. Figure 6.7 is a conceptual example of the interrelationships between nanoscale and microscale fabrication.

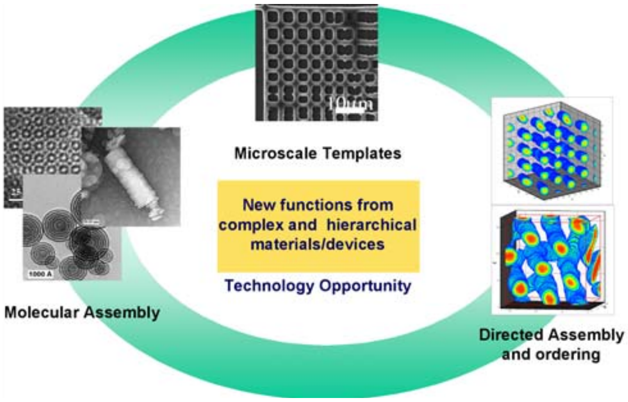

Figure 6.7. Relationships between top-down (microscale templates) and bottom-up (molecular assembly) fabrication approaches for nanoscale devices (courtesy of NASA) [3].

A major issue in manufacturing is the packaging of nanotechnology-enabled devices. The packaging cost typically can be as much as 70 percent of the cost of a sensor. Not only can the packaging be expected to be different for each device, but also for different applications of the same device, resulting from various demands for space, power, environment, and communication of information to the outside world.

System-Level Reliability Testing

Although this is an important and essential "gate" for all new technologies to pass through for space system implementation, system-level reliability concerns are often ignored in the early development phase and only thought of when it is already too late. System-level reliability testing is applied routinely for the qualification of new products in the commercial sector. For a new nanotechnology-based system to achieve the maturity necessary for relevant environment (space) testing, a robust manufacturing process must be in place. Implicit in achieving this level of maturity is the absolute requirement that fabrication, assembly, testing, and characterization processes for these systems must be well established. A large number of parts must be available for statistical quality control analysis purposes. Special testing procedures and tools must be devised in order to properly assess the reliability of these nanotechnology-based systems.

System-Level Manufacturing Standards

As the system development process becomes more mature, the need to establish standards for the manufacturing and testing of these new technologies becomes critical. As described above, organizations such as NIST have started on the path to developing standards for nanotechnology-based systems. However, a considerable amount of work remains to be done in establishing standards for such a vast range of products. In particular, within the context of this discussion, a clear set of standards must be set for nano-micro-macro interfaces.

Technology Maturation Team Approach to System Development

It is extremely important that a "technology maturation team" (TMT) approach be followed in order to ensure successful, system-level development of nanotechnology-based systems. The TMT, formed early in the system-level development phase, typically consists of the end-use customer, reliability assurance personnel, system developers, the nanotechnology inventor, and the investor. As shown below in examples presented at the NNI workshop, achieving a useable system at a maturity level consistent with flight requires many disciplines. It also requires new knowledge and tools to achieve levels of consistency in materials, design, fabrication, and integration to take the potential of nanotechnology into the real world of flight hardware. Once the proof of principle for the novel nanoscale phenomenon has been demonstrated in the laboratory, the TMT should be constituted in order to shepherd the new technology through the system development process culminating in space application insertion. The TMT approach to system development will bring all of the skill sets necessary for the nano-micro-macro integration.

Solutions

Perhaps the best way to approach the challenges described above is to discuss the lessons learned from the implementation of new technologies on the Space Shuttle as presented by David Bartine of NASA Kennedy Space Center and Pedro Medelius of ASRC Aerospace Corporation. The essence of their discussion was to give guidelines for the infusion of new hardware as a flight item on the Shuttle. The issue is really one of whether the system provider has satisfied the performance and compatibility requirements of the end-user. Implementation of a new technology often fails, not because of a failure of the technology's intrinsic performance, but because it does not match the form, fit, function, and compatibility requirements of system-of-systems end application. For this reason, program managers from industry and from the space agencies responsible for procuring new technology systems are very conservative. Consequently, most technologies flown on spacecraft today may be at least a decade old. Therefore, as reflected in the TMT section above, based on their extensive Space Shuttle experience, Bartine and Medelius made the following recommendations:

- Form the team early and include both technology developers and end users
- Identify the application niche for the new technology and ensure that it is well defined
- The new system should demonstrate that:
  - The new technology works well within the environment in which it will be used
  - The new technology presents no danger to other parts of the system (i.e., is compatible)
- The system provider works closely with the user throughout the entire acceptance process

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7. ASTRONAUT HEALTH MANAGEMENT

Breakout Session Co-Chairs: Antony S. Jeevarajan and R. Kelley Bradley

VISION

The ultimate vision for nanotechnology in astronaut health management is to provide a quality of life, a quality of human performance, and a quality of medical care equivalent to that on Earth, regardless of the type or duration of the space mission. This is the vision for a large-scale, sustainable human presence in space. Nanotechnology will be an enabler for this vision for two primary reasons: first, nanotechnology products will follow the "better-stronger-lighter-cheaper" paradigm; second, many of the challenges to astronaut health management can be related to nanoscale phenomena and therefore must be met with solutions provided by nanotechnology. The following is a list of vision statements that support the overall vision for nanotechnology in astronaut health management. The vision statements were derived based on needs only. As a result, the scope and level of challenge vary between statements. Although the vision statements are described in terms of the results desired, it should be understood that nanotechnology will play the key role in the research leading to the final accomplishment of the visions.

Pharmaceutical Countermeasures

A thorough understanding of the effects of the space environment at the tissue, cellular, and sub-cellular levels will be developed, and key mechanisms by which deleterious conditions arise will be identified. Pharmaceutical countermeasures to these conditions will be developed that will allow astronauts to minimize risk of illness. These pharmaceuticals will be "smart drugs" based on the nanomedicine paradigm and will harness the machinery of the cell to produce *in situ* active ingredients. Pharmaceuticals' shelf life will be extended and the issue of reduced shelf life in space will be solved.

Self-Sufficient Medical Care

Medical care will be elevated to the level of complete self-sufficiency, including the ability to perform surgery and the capability to deal with trauma and related events. Most medical procedures will be performed by, or aided by, automated medical devices. Medical devices for monitoring, imaging, and performing assays will be developed in a small and lightweight form. Capabilities will include sequencing the patient's genome for pre-screens, massive simultaneous assays for infection or markers (such as stress proteins) indicating physiological states, and various handheld imaging devices such as high-resolution ultrasound and portable computed tomography (CT).

Benefits Beyond the Space Environment: The technology developed for astronaut health management will be of use in other hazardous environments and critical need areas where health management is required, such as fire fighting, battlefields, submarines, emergency rooms, potential high radiation environments, and isolated locales. There are many similarities between health management issues on Navy submarines and manned spacecraft, and there is the potential for strong synergy between these two programs. Additionally, the needs of the space program will drive nano-health management faster than it would otherwise develop, exemplifying the role of government agencies in "jump-starting" new technology into the private sector.

Environmental Control

Spacecraft will have closed-loop environments with the ability to reclaim air and wastewater. Environmental sensors distributed throughout the ship will keep track of contaminants in the air and water. Personal chemical dosimeter badges will track exposure of individual astronauts. Nanomaterials will aid in space vehicle construction by cutting down on the amount of outgassing that occurs and by improving filters and scrubbers.

Human Factors

Astronauts will be provided with a work environment that is comfortable and tailored to help maintain mental acuity. This will include intuitive interfaces with the space vehicle and with their equipment. Nanomaterials with antimicrobial properties will be used throughout the vehicle to help prevent the build-up of microbes in the environment. This includes clothing that will require little or no washing due to specially engineered materials constructed and/or treated using various surface chemical modifications.

Radiation Shielding

Effective lightweight radiation shielding material will be developed. There will be no danger of radiation exposure while inside the space vehicle or in space. More effective materials will be developed for extravehicular activity suits to reduce levels of exposure. Pharmaceuticals will be developed to help repair damage from radiation.

STATE OF THE ART

Nanotechnology for astronaut health management covers a wide variety of research topics. The following topics were selected in an attempt to extract common concepts employed by the workshop participants in their research.

Nanoparticles

In this case we use the term “nanoparticles” loosely to cover nanostructures such as small colloidal particles, dendrimers, liposomes, nanoshells, nanotubes, quantum dots, etc. Nanoparticles are an ideal platform for bottom-up nanotechnology. They provide intrinsic functionality and act as a nanoscale chassis onto which various moieties can be attached in order to provide additional functionality. Nanoparticles are particularly well suited for nanomedicine applications because their size allows them to be easily distributed throughout the body and to be taken up by cells. Technology development in recent years has allowed for synthesis of various types of nanoparticles that are now commercially available. Research areas such as the creation of core shell particles, enhancement of optical properties, and creation of complex multifunctional nanoparticles are being explored currently. Despite continuous progress in this field, key issues are still present and include nanoparticle suspension in liquids, particle aggregation, and chemical modification.

MEMS (Microelectromechanical Systems)

Here MEMS is loosely used to include nanoelectromechanical systems, non-electromechanical (passive) micromachined structures, as well as traditional MEMS. MEMS are the top-down analogue to nanoparticles and can provide an interface to the macroscale world through electronic, mechanical, optical, or microfluidic means. While MEMS devices can have intrinsic functionality, they can also act as a substrate for attaching moieties to provide additional functionality. Some

MEMS devices are commercially available, such as microgrippers and AFM probes. Many nanofabrication facilities, such as the Stanford Nanofabrication Facility, are accessible on-line through the National Nanotechnology Infrastructure Network and are available to all researchers.

Integration of Natural Bionanomachinery

The cell is an existence proof of nanomachinery (Fig. 7.1). For example, ribosomes are nanoassemblers that convert information from mRNA into functional protein molecules. Biotechnology has already made great use of functioning bionanomachines, such as antibodies, in immunoassays. Nanotechnology will extend the use of natural bionanomachines much farther. A few examples include modifying existing bionanomachinery to change their activity, harnessing information processing biomolecules to create nanoscale switches and sensors, and using biological modes of recognition and delivery, such as antibodies and viruses, to deliver treatment to individual cells.

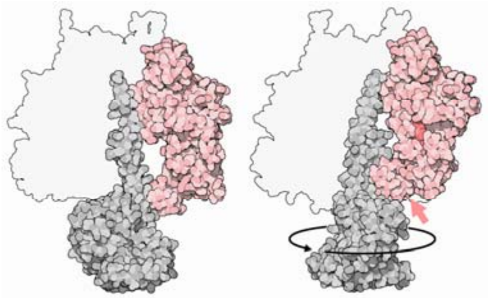

Figure 7.1. Natural bionanomachines are an existence proof for nanotechnology: ~10,000 working nanomachines are in a typical cell. Structures of 1,500 unique protein domains are in the Protein Data Bank (courtesy of David Goodsell, Scripps Research Institute).

Many proteins and biomolecules are commercially available in a purified form. Novel devices have been made using molecular motors. The Avidin-Biotin complex is a common model system used for highly specific recognition and binding interactions, much like the antibody-antigen binding that occurs in the body. Natural biomolecules such as insulin and growth hormones created by biotechnology are currently in widespread use for replacement therapy. Tailored antibodies are used for biosensing in medical diagnostics. Hybrid biomolecules composed of biosensing and cytotoxic functions are used for cancer therapy.

Bio-Nano-Info Convergence

Bio-nano-info convergence has three important roles in astronaut health management. First, it is important that nanoscale signaling, which occurs naturally within our cells, be of sufficient fidelity. Since nanoscale signals are very noisy, methods need to be developed to improve signal output. The second role is data handling. The convergence of nanotechnology and biotechnology will result in clinicians having access to an unprecedented amount of data on an individual. Handling and interpreting these data will be a challenge. For example, how will a medical problem be differentiated from a benign anomaly that would have been overlooked without nanotechnology-based monitoring? The third role is in automation, which is particularly important in the space program where astronauts may not have the time or the medical expertise to handle every medical procedure that is required.

Targeting and Signal Fidelity in Nanomedicine: To deliver a drug to a specific type of cell, it is critical to have adequate specificity. Choosing one surface receptor may not provide the required specificity; two or more receptors may be required. Understanding how to maintain fidelity in the signal, in this case accurate cell targeting, is crucial to effective nanomedicine.

From the perspective of the biological sciences that are focused on nanoscale phenomena (e.g., molecular biology, biochemistry, neurosciences, and cell physiology), the understanding of information provides a basis for understanding both the molecular details (quantum effects) and the ensemble. It is with the tools of information science that whole genomes are mapped, biochemical reactions are simulated, neurological pathways are reconstructed, and cell processes are modeled. Developments in nanomedicine for monitoring and intervening on the nanoscale would provide new possibilities to understand and alleviate pathologies. Technology has been developed for combinatorial techniques in biology and chemistry. A great deal of theoretical work has been done on signal processing in the electronics industry. A large part of cell biology research is dedicated to studying signaling pathways in cells.

Biocompatibility and Toxicology

Biocompatibility and toxicology are extremely important for the development of nanomedicine and to protect the health of those who come into contact with nanomaterials. Understanding the fate of nanoparticles in the body and whether they are taken up into cells is of crucial importance in nanomedicine. Determining if there are detrimental effects from nanomaterials on tissue and cells is very important as these materials begin to be used. It is important that the entire lifetime of the material be considered. For instance, a nanoparticle in a polymer composite may eventually become free of the composite through wear over its lifetime. Ongoing efforts include studying the effects of nanotubes and fullerenes as well as the biodistribution and toxicity of colloidal particles. Public awareness and the development of standards must become intrinsic parts of this effort to create the public trust that nanotechnology will be developed in a responsible manner. The nanotechnology community is making strides to communicate with the public on such safety issues.

Internal Monitoring and Imaging

This topic and the External Assays and Sensors topic are closely related. They have been somewhat arbitrarily divided into two groups pertaining to data collection inside the body on one hand and outside the body on the other. Monitoring and imaging covers contrast agents and reporters that are injected into the body and provide data to outside sensors. This topic is closely related to issues of biocompatibility. Non-invasive and quasi-non-invasive monitoring and imaging are also important aspects of this topic. Much work is being done on developing nanotechnology-based contrast agents for CT imaging and nuclear magnetic resonance (NMR) imaging. Micromachined ultrasound devices have greatly improved performance over existing technology.

External Assays and Sensors

This topic pertains to biological assays on body fluids, such as saliva, urine, and mucus. Drawing blood, a common procedure with terrestrial patients, is rarely performed in space due to zero gravity. The topic also covers chemical sensors for monitoring trace contaminants in the space vehicle’s air and water supplies. Ongoing work includes developing techniques to rapidly sequence DNA and to identify biomolecules using nanoelectrodes and nanotransistors. Many research groups around the world are studying novel sensor modalities for the development of ultra-sensitive and selective nanosensors.

Basic Space Life Science Research

Despite continued progress in this area, much is yet to be discovered about the effects of the space environment (microgravity and radiation) on astronauts. Part of the challenge lies in the difficulty of accessing microgravity for experimentation. Another present difficulty is to study the effects of mechanical perturbation due to microgravity at the cellular level. It is also important to understand the effects of the space environment on microorganisms that could result in infections in humans; some microorganisms may actually become more aggressive or resilient to treatment.

Drug Delivery

Delivering drugs where and when they are needed vastly improves therapies and in some cases is the only way that a therapy can work properly. MEMS and colloidal-based drug delivery devices are being developed.

Nanosystems for Continuous Astronaut Health Monitoring in Space

Dr. James Leary (University of Texas Medical Branch in Galveston) is developing a nanomedicine system based on multilayered nanoparticles and bionanomachinery used as sensors and triggers. Each layer of the nanoparticle is biodegradable and has an active moiety attached to it. As the layers degrade one-by-one, they activate the next moiety in the sequence. For example, the outer layer has an antibody attached to provide cell targeting, and the next layer has a moiety attached to provide targeting within the cell. The layer below that is a biological sensor consisting of a nucleic acid sequence with a promoter region that can be activated by a protein inside the cell in response to genetic damage from radiation. The promoter then allows expression of the drug encoded on the nucleic acid strand to manufacture therapeutic genes *in situ*.

VisiGen Real-Time DNA Sequencing

Dr. Susan Hardin and colleagues at VisiGen are developing a technique to sequence the entire human genome in about 1 hour for about $1,000. The technology is a fusion of biology, electronics, and information systems. The VisiGen process (Fig. 7.2) exploits the biochemistry of DNA replication and uses modified versions of polymerase and nucleotides to determine the DNA sequence. More specifically, the polymerase is labeled with a “donor” fluorescent molecule that

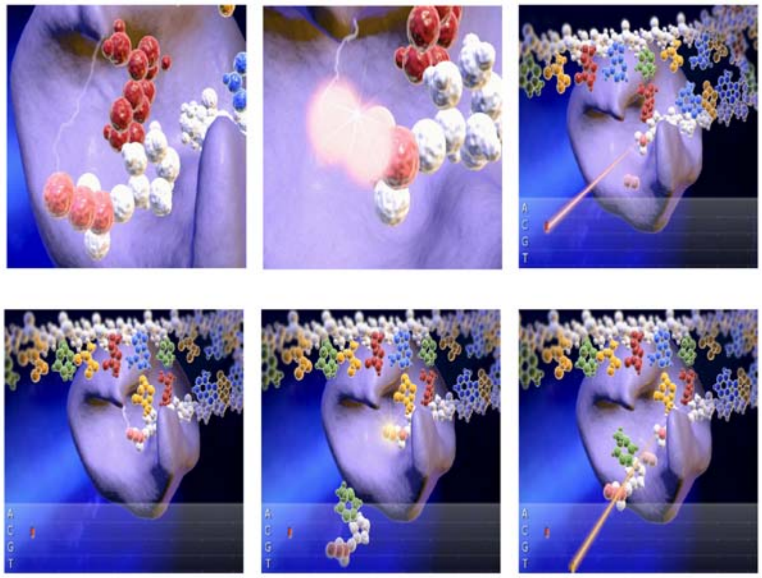

Figure 7.2. Artist’s conception of VisiGen process. A polymerase enzyme assembles a double-stranded DNA. The lightning bolts represent energy transfer from the donor fluorophore on the polymerase to an acceptor fluorophore on the incoming nucleotide. The light beams represent fluorescence from the acceptor fluorophore to the detector uniquely identifying the nucleotide by color (courtesy of Dr. Susan Hardin, VisiGen Biotechnologies, Inc.).

comes into close proximity with an "acceptor" labeled nucleotide during DNA assembly. Four different acceptor fluorescent molecules are attached to the terminal phosphate group on each nucleotide type, creating color-coded nucleotides. The donor is excited by a laser to transfer energy to an acceptor that is in turn excited and fluoresces during nucleotide incorporation. In this way it is possible to watch the fluorescence signal as each nucleotide is added to the growing strand. As the nucleotide is incorporated into the chain, the acceptor fluorophore and phosphate group are ejected, leaving the growing chain in its natural state. This technology relies on single-molecule spectroscopy to determine the data from individual sequencing nanomachines. These machines are arranged in massively parallel arrays to obtain the high throughput needed to sequence a genome in about an hour.

Nanobacteria

Dr. Neva Çiftçioğlu of Universities Space Research Association is studying self-replicating hydroxyapatite nanoparticles known as nanobacteria (NB). Nanobacteria (Fig. 7.3) appear to show a correlation with such diverse conditions as arterial heart disease, Alzheimer's disease, kidney stone formation, polycystic kidney disease, and malignant tumors. Furthermore, these NBs (size ~100 nm) have unique properties including very slow replication rate (~3 day doubling rate), rapid *in situ* precipitation of calcium phosphate (biomineralization) from blood and other body fluids under conditions not normally conducive to such precipitation, and the apparent ability to extract and concentrate phosphorous from dilute solutions. Biomineralization in soft tissue, called pathological calcification, is a major problem in 25 percent of human diseases (e.g., atherosclerosis, kidney stone formation, and cancer). Astronauts have experienced an increase in kidney stone formation after long-duration missions at zero gravity. Dr. Çiftçioğlu is investigating the role nanobacteria play and how microgravity affects them.

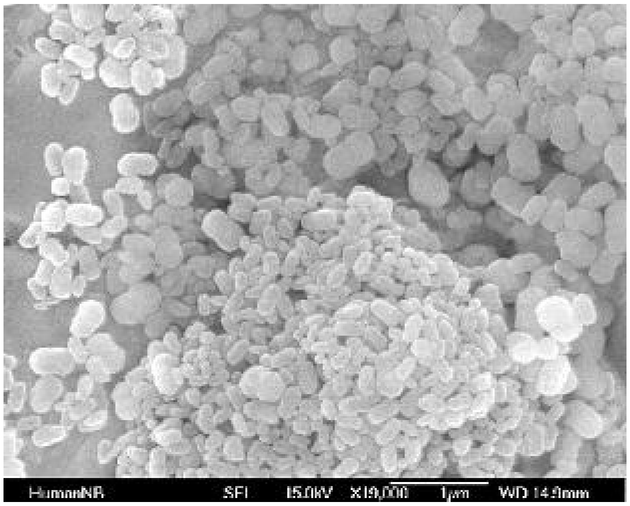

Figure 7.3. Scanning electron microscopic image of cultured nanobacteria from human blood. Bar: 1 μm (courtesy of NASA).

MEMS Bioartificial Kidney

Dr. Shuvo Roy of the Cleveland Clinic and colleagues at the University of Michigan Medical School are developing a miniature bioartificial kidney that will be applied to wounded soldiers suffering from acute renal failure. Mortality rates from acute renal failure in wounded soldiers in Vietnam were over 60 percent despite early and frequent dialysis. Evidence from chronic dialysis patients associates kidney failure with immune suppression, oxidative stress, and chronic alteration of cytokine levels. Clearly, dialysis does not provide the metabolic, endocrine, and immunologic functions of a healthy, natural kidney. Therefore, the goal of tissue engineering of an artificial kidney incorporating living kidney cells as well as filtration should provide complete renal replacement.

In addition to performing filtration, the renal assist device (RAD) incorporates a proximal tubule bioreactor to more closely mimic a natural kidney (Fig. 7.4). In laboratory animals, the RAD has recently been demonstrated to ameliorate the cardiovascular effects of septic shock, minimize

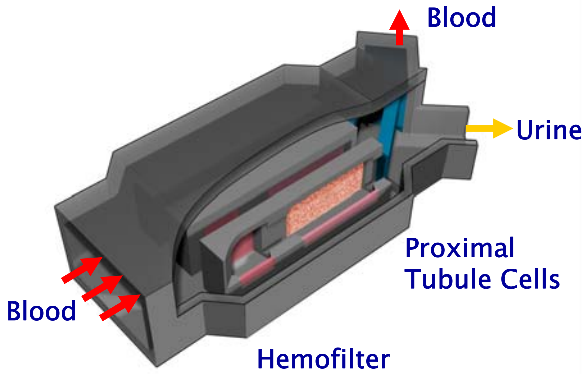

Figure 7.4. Renal assist device (courtesy of NASA).

infection, and delay mortality. The first two human patients in a Phase I clinical trial of the RAD showed extraordinary improvement in health and were discharged alive with complete recovery of kidney function. However, the conventional RAD is a large system that requires a space of dimensions 12 × 10 × 8 ft. as well as specialized personnel for operation. Consequently, a miniature, compact, and low-cost version of the RAD for deployment in treatment of combat casualties is currently under development. A critical component is the hemofilter, which is nanofabricated from a silicon wafer with slit pores 20 nm wide. Proximal tubule cells are grown on cartridges that can be replaced in the unit. The "nano-enabled" device is lightweight and portable, making it of great potential value in military field hospitals for combat casualties as well as in chronic renal failure patients awaiting kidney transplants. This miniature RAD is particularly amenable to space exploration since it could substantially increase the survivability of astronauts subjected to trauma and shock, which in turn can result in renal failure.

Contrast Agents

Dr. Ananth Annapragada from the University of Texas Houston is developing long-lived contrast agents for computed tomography based on Stealth® liposome technology. Liposomes are artificial vesicles used for drug delivery. Dr. Annapragada is investigating methods to extend the working time of contrast agents used for CT imaging. In collaboration with Dr. Srini Mukundan and Dr. Allan Johnson at Duke University, they have acquired the first dynamic blood pool images in small animals, including the ultra-small features of heart chambers and tumors (Fig. 7.5). Dr. Annapragada is also developing a "smart" therapeutic approach based on agglomerated vesicle technology (AVT) particles, which can modulate drug release in the lung upon demand (Fig. 7.6). His group has demonstrated the modulated release of both insulin and ciprofloxacin in the lung, paving the way to non-invasive, smart therapeutic dosages of these drugs.

Figure 7.5. Longitudinal slice of mouse thorax showing heart and chambers (CT image courtesy of NASA).

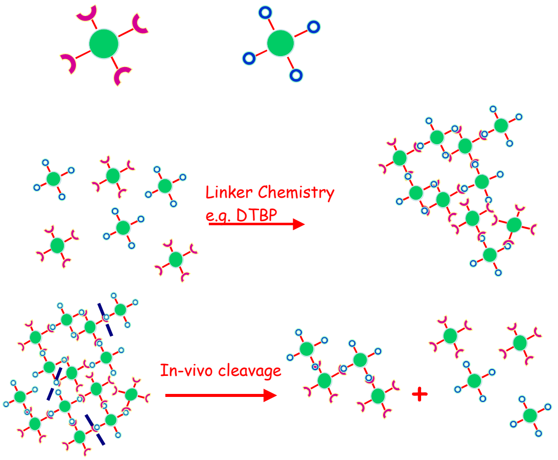

Figure 7.6. Modulated release of drug from AVT particles. Internal or external agents trigger release (courtesy of NASA).

Nanotransistors

Dr. Louis Brousseau of Quantum Logic Devices is developing diagnostic and sensor technology based on ultra-sensitive quantum dot transistors. A capture biomolecule such as a single-stranded DNA or antibody is attached to the quantum dot (Fig. 7.7). The voltage versus current profile of the device changes when the target is captured (e.g., the complementary DNA strand or the antigen). The advantage of this technique is that no fluorescent markers are required to perform the assay, enabling the use of opaque and scattering samples, including urine, saliva, plasma, etc. Fluorescence-based systems are limited in how many targets can be detected simultaneously by the spectra width of the fluorophores used and are encumbered by bulky instrumentation requirements. With the nanotransistor system, it is possible to assay large numbers of targets simultaneously on one small chip. These chips can then be placed on very small devices such as tongue depressors or handheld analysis units.

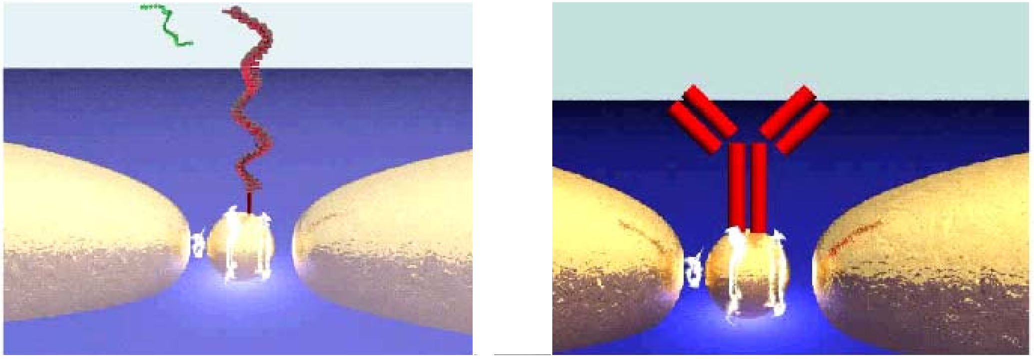

Figure 7.7. Sensor technology based on ultra-sensitive quantum dot transistors (courtesy of NASA).

Nanoelectrodes

Dr. Jun Li of the NASA Ames Research Center is working on highly sensitive electrochemical sensors based on conducting carbon nanotube arrays. Nanotubes are grown vertically off of a lithographically patterned surface via a chemical vapor deposition reaction. The nanotubes are then over-coated with a layer of silica, and finally the silica layer is polished to expose the tips of individual nanotubes. Because the exposed portion of the nanotube is so small, it creates an ideal electrode with radial diffusion of ions, resulting in very low hysteresis in the voltammetric spectra and extremely high levels of sensitivity. A single nanotube would be too susceptible to noise but using nanotube arrays overcomes this problem and provides a reliable signal. Dr. Jun Li has developed this technology into a biosensor by attaching capture molecules to the electrode and sensing the electrochemical shift that occurs when the target is present. This technology has been developed into a hand-held chip-based array device (Fig. 7.8).

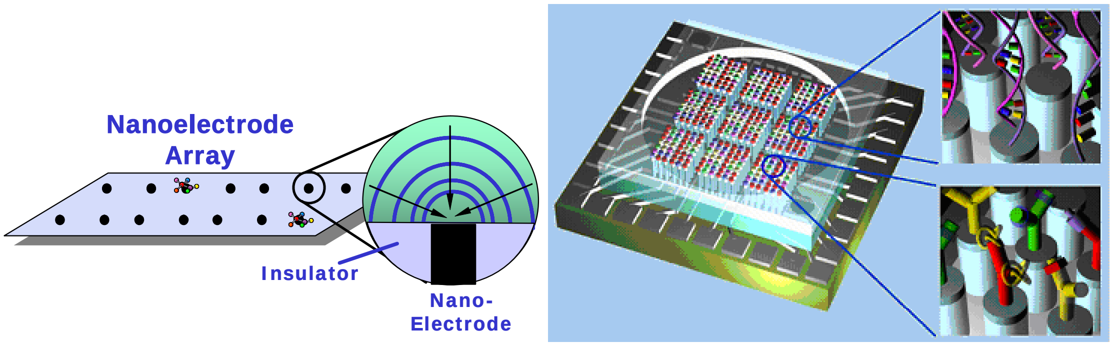

Figure 7.8. Highly sensitive electrochemical sensors based on conducting carbon nanotube arrays (courtesy of NASA).

Surface-Enhanced Raman Scattering

Nanostructures open up exciting new directions in optical spectroscopy, as they can provide enhanced local optical fields where spectroscopy takes place. The unexpectedly high Raman scattering signal from molecules attached to nanoscale silver and gold structures, known as surface-enhanced Raman scattering (SERS), is one of the most impressive effects (Fig. 7.9). Dr. Katrin Kneipp from Harvard Medical School is developing ultra-sensitive sensing technologies based on SERS, which have the potential of providing molecular information using tiny volumes (nanoliters). Applications include monitoring molecular structural changes in cells with the potential of detecting radiation damage in particular and physiological monitoring in general. In addition, quantification of molecules relevant to biomedicine such as neurotransmitters, as well as analysis of trace contaminants and chemical characterization of substances in non-terrestrial environments, are areas that are being explored. The SERS sensing technology has the capability of fast, accurate, and high-throughput detection. Furthermore, this technology allows for building portable operating systems, simple interpretation of the output data and can be managed by un-trained personnel. SERS active substrates (nanostructure + target molecule) can be stored for documentation and for further measurements after the space mission is completed.

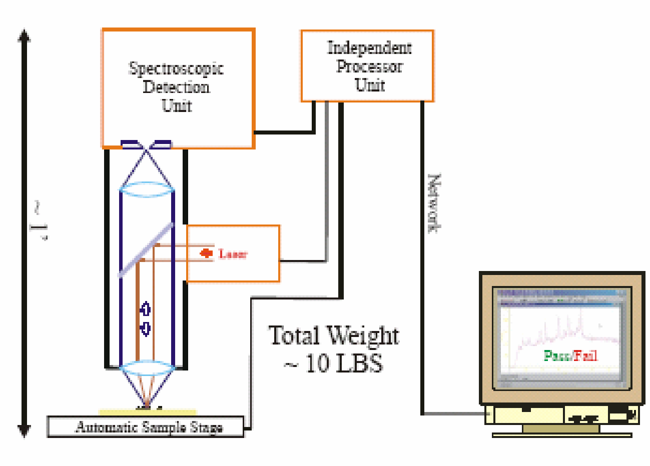

Figure 7.9. Diagram of SERS sensing system (courtesy of Katrin Kneipp, Harvard Medical School) [1].

MAJOR CHALLENGES

Barriers and Solutions

As we begin to contemplate the first steps towards permanent human presence in space that is beyond the range of immediate medical help from the Earth, there are some major challenges to astronaut health management to consider [2, 3]. Nanotechnology will play a crucial role in meeting these challenges. In this document, the term *astronaut health management* is used broadly to include the entire effort to keep humans healthy in space. Examples of what is included under this umbrella are biomedical technologies, pharmaceuticals, medical instruments, and environmental systems that will be built upon the underlying basic research in space life sciences and nanotoxicology/biocompatibility. The following list represents the challenges that NASA will have to face in its upcoming moon and Mars missions as well as in the ongoing operation of the International Space Station and the Space Shuttle fleet. The challenges listed below are those in which there is a high probability that nanotechnology will play a significant role.

Communication Lag

The farther away astronauts travel, the longer the communication lag becomes. This means that the astronauts must be able to perform autonomously any operations that require rapid response to changing conditions.

Expertise

Keeping in mind the limited crew size, limited medical training, and the limitless number of medical/health eventualities that the crew could face, it must be assumed that there will be situations in which the crew is not fully prepared. Hence, there must be procedures in place to train the crew during a space flight.

Engineering Constraints

Though crew health is of critical importance, engineering constraints will often be of higher priority. For example, there may be limits to the amount of oxygen that can be given to an injured crewmember before oxygen levels in the ship reach the point of fire hazard. Engineering constraints can be a major challenge in terms of instrument design and medical protocols.

Water Usage

By mass, water accounts for most of the consumables used to support human life. The basic necessities per day are 1.0 kg oxygen, 0.5 kg dry food and 3.4 kg of water, including water in the food and water used to prepare it. If accounting for showers and washing of clothes, the amount of water required per day increases to roughly 30 kg. This large amount of water would have to be brought with the crew for the duration of the mission, severely increasing the overall launch mass. The challenge is to find ways to use less water during a mission.

Bone Density Loss

Astronauts can experience loss of bone density at a rate as high as 1.6 percent per month under microgravity conditions and, upon transition to higher gravity, bone fractures can occur. This is a serious problem for astronauts traveling to and returning from Mars. The challenge is to mitigate the risk of bone fracture.

Radiation Exposure

Astronauts on Mars missions will be exposed to space radiation for extended periods of time. They must be effectively shielded or otherwise protected from the carcinogenic and tissue-damaging effects of radiation.

Closed-Loop Environment

For long-duration missions, it will be necessary to use a closed-loop environment; however, there is an increased risk that contaminants will build up much more rapidly than in an open-loop system. Therefore, the environment must be constantly monitored for contaminants and effectively filtered and purified.

Psychosocial Adaptation

Astronauts live under conditions in which they are stressed physically and mentally. Loss of mental acuity can reduce work efficiency and, in certain situations, pose a risk to life.

Limited Medical Resources

Current medical resources in space are limited and crewmembers suffering from serious medical problems are returned to Earth for treatment, which will be impossible in the case of long-duration missions. New technologies must be developed that allow for surgical operations in microgravity conditions.

Microgravity

Microgravity presents many complications to processes that are taken for granted on Earth. For instance, conventional intravenous (IV) bags do not work without gravity present. Furthermore, microgravity has deleterious physiological effects on astronauts. Understanding the mechanisms behind these conditions is a challenge that will lead to the development of countermeasures.

Solutions

- A better understanding of the basic science behind the effects of the space environment on the astronaut’s body is needed.
- Fostering interdisciplinary connections between researchers in different fields (engineers, scientists, clinicians, etc.) will help accelerate the implementation of nanotechnology applications to space flights.

GOALS

5–10 Years

- Develop pharmaceuticals to enhance radiation repair mechanism in cells
- Develop pharmaceuticals with extended shelf life in space
- Develop lightweight, automated diagnostic equipment for high-throughput analysis of biomarkers and infectious agents
- Develop lightweight, automated imaging equipment with dual use for medicine and engineering
- Develop methods for environmental monitoring of air and water

- Collect and interpret data to develop pharmaceutical countermeasures for bone density loss
- Develop antimicrobial materials to prevent the growth of bacteria or fungi in the space vehicle and to reduce the amount of water needed to wash clothes
- Develop ground-based screening techniques to select astronauts who are more resistant to radiation and microgravity
- Form and maintain good relationship with the public, and disseminate information about the safety and usefulness of nanomaterials and devices

Beyond 10 Years

- Pharmaceutical prevention of all negative affects of space environments
- Automated total health monitoring and diagnostic equipment
- Complete medical self-sufficiency, including the ability to perform surgery
- Complete reclamation of waste and control over sealed environments

CONCLUSIONS

In NASA's new Vision for Space Exploration, there are many challenges to astronaut health management. Nanotechnology will make significant contributions towards meeting these challenges. The space program can play an important role in driving some of the more visionary aspects of biomedical nanotechnology forward faster than might otherwise occur. NASA can help foster the development of these technologies while at the same time meeting its own needs for exploration.

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2. Lockheed Martin Space Operations and NASA, *Bioastronautics Critical Path Roadmap (BCPR) Draft*, (2004) (available at http://research.hq.nasa.gov/code_u/bcpr/index.cfm).
3. J. R. Ball, C. H. Evans, Jr., *Safe Passage Astronaut Care for Exploration Missions*. Washington, DC: National Academy Press (2001).

APPENDIX A. WORKSHOP AGENDA

DAY ONE (AUG. 24): HYATT HOTEL, BALLROOM—PALO ALTO

8:00–8:30	Registration/Continental Breakfast
8:30–9:00	Scott Hubbard, Director, NASA Ames (Welcome and Opening Remarks)
9:00–9:30	Clayton Teague, Director of NNCO (NNI Overview)
9:30–10:15	Stan Williams, Hewlett Packard (Fault- and Defect-Tolerant Nano-Electronics for Memory and Processing)
10:15–10:30	*Break*
10:30–11:00	Terry Allard, NASA Headquarters (Exploration Vision)
11:00–11:30	Minoo Dastoor, NASA Headquarters (Nano for Space Exploration)
11:30–12:00	Congressman Mike Honda (Nanotechnology Legislation)
12:00–1:30	*Lunch* Hyatt Hotel, Palo Alto
1:30–5:00	Breakout sessions with Invited Talks
6:00–7:00	Networking Reception
7:00–8:30	*Dinner* Speaker: Chris McKay (Nanotechnology for Astrobiology Missions in the Solar System)

DAY TWO (AUG. 25): HYATT HOTEL, PALO ALTO

8:00–8:30	Registration/Continental Breakfast
8:30–5:00	Breakout sessions with Invited Talks

DAY THREE (AUG. 26): HYATT HOTEL, PALO ALTO

8:00–8:30	Continental Breakfast
8:30–11:00	Report from Session Chairs on Breakout Sessions
11:00–12:00	Discussion

BREAKOUT SESSIONS: AGENDA

1. NANOMATERIALS (Edwards Room)

August 24, 2004

Structural

1:30–1:50	*Mia Siochi*—Langley Research Center
1:50–2:10	*Ilhan Aksay*—Princeton University
2:10–2:30	*Deepak Srivastava*—University of California, Santa Cruz Theory and Simulations
2:30–5:00	Discussion

August 25, 2004

Non-Structural

8:30–8:50	*Mike Meador*—Glenn Research Center Fuel Cells, Batteries, etc
8:50–9:10	*Duncan Stewart*—Hewlett Packard Electronics/Sensors
9:10–9:30	*Jonathan Trent*—NASA Ames Research Center Bio/Bio Inspired Materials
9:30–12:00	Discussion

Multifunctional for Aerospace

1:30–1:50	*Jim Arnold*—University Affiliated Research Center (NASA) Thermal, Radiative and Impact Protective Shields
1:50–2:10	*Ray Baughman*—University of Dallas Composite Fibers and Fabrics
2:10–2:30	*Stephenie Hooker*—National Institute of Standards and Technology Manufacturing and Metrology for Nanomaterials
2:30–5:00	Discussion

2. MICROCRAFT (Governor's Board Room A)

Brian Wilcox—Jet Propulsion Laboratory

Ernest Robinson—Aerospace Corporation (Retired)

Robert Twiggs—Stanford University

David Klumpar—Montana State University

3. MICRO/NANO-ROBOTICS (Marsten Room)

August 24, 2004

1:30–2:15	*Kris Pister*—University of California, Berkeley, and Dust, Inc. Micro-Robots & Smart Dust
2:15–3:00	*Jim von Ehr*—Zyvex Micro- and Meso-Scale Robotics
3:15–4:00	*Jacob Schmidt*—University of California, Los Angeles Bio-Nano-Robotics
4:00–5:00	Discussions

August 25, 2004

8:30–9:15	*Seth Goldstein*—Carnegie Mellon University Claytronics—Self-Reconfigurable Miniature Robots
9:15–10:00	*Russell Taylor*—University of North Carolina Nanomanipulation
10:15–11:00	*Metin Sitti*—Carnegie Mellon University Micro- and Nanoscale Robotics
11:00–12:00	Discussions
1:30–3:00	Discussions
3:00–5:00	Report Writing

4. NANO-MICRO-MACRO INTEGRATION (Holtum Room)

August 24, 2004: No Session

August 25, 2004

8:30–8:50	Introduction by Session Chairs
8:50–9:10	*Neal Shinn*—Sandia National Lab
9:10–9:30	*Raymond Mariella Jr.*—Lawrence Livermore Lab
9:30–9:50	*Suraj Rawal*—Lockheed Martin
10:00–12:00	Discussion
1:30–1:50	*Arun Majumdar*—University of California, Berkeley
1:50–2:10	*Brian Hunt*—Jet Propulsion Laboratory
2:10–2:30	*John Lekki*—NASA Glenn Research Center

2:30–2:50	*Minoru Freund*—Wright-Patterson Air Force Base
3:00–5:00	Discussion

5. SENSORS AND INSTRUMENTATION FOR SCIENCE MISSIONS
(Stanford Room)

Intro/Lessons Learned (Chair: Sean Casey)

August 24, 2004

1:30–1:45	*Sean Casey*—Universities Space Research Association Instruction to participants
1:45–2:00	*Tim Krabach*—Jet Propulsion Laboratory Sensing in the Nano World
2:00–2:15	*David Bartine*—NASA Kennedy Space Center Orbiter Lessons Learned?
2:15–2:30	*Joseph Stetter*—Trans. Tech/Illinois Institute of Technology Nano-Sensor Agenda
2:30–2:45	*David Blake*—NASA Ames Research Center XRD/XRF Instrument
2:45–3:00	Group Discussion
3:00–3:15	Break

Chemical (Chair: Mary Zeller)

3:15–3:30	*Brian Hunt*—Jet Propulsion Laboratory Nanowire Chemical Sensors
3:30–3:45	*Gary Hunter*—NASA Glenn Research Center Chemical Sensors Aero/Applications
3:45–4:00	*Pedro Medelius*—Aerospace Center Sensor Development
4:00–4:15	*Benjamin Sullivan*—University of California, San Diego Assembly of Nanostructures
4:15–4:30	*Sudipta Seal*—University of Florida Nanostructures for H-sensors
4:30–4:45	*Nicholas Prokopuk*—Naval Air Warfare Center Infinitesimal Chem-sensors
4:45–5:00	Group Discussion
5:00	End of Session

Electronics (Chair: Pedro Medelius)

August 25, 2004

8:30–8:45	*Nick Melosh*—Stanford University Resonant Detection
8:45–9:00	*Jim Morris*—Portland State University Room Temperature SETs
9:00–9:15	*Neal Watkins*—NASA Langley Research Center Semi-Properties of CNTs
9:15–9:30	*Tinh Nguyen*—National Institute of Standards and Technology Imaging Hetero-Nano Surfaces
9:30–9:45	*Cattien Nguyen*—ELORET Corp. CNT AFM Probe Tips
9:45–10:00	Group Discussion
10:00–10:15	Coffee Break

Photonics (Chair: Benny Toomarian)

10:15–10:30	*Sarath Gunapala*—Jet Propulsion Laboratory Qdot Detectors and Lasers
10:30–10:45	*Holger Schmidt*—University of California, Santa Cruz Nanopore Waveguides
10:45–11:00	*S. K. Sundaram*—PNN Lab Chalcogenide Nanostructures
11:00–11:15	*Paul Drzaic*—Alien Technology Fluidic Self-Assembly
11:15–11:30	*Steve Arnold*—Polytechnic University Whispering Mode Bio-sensor
11:30–11:45	Group Discussion
12:00	End of Session

New Instruments (Chair: Peter Shu)

1:30–1:45	*Bharat Bhushan*—Ohio State Nanotribology
1:45–2:00	*John Cumings*—Stanford University *In situ* Electron Microscopy of the Operation of Nanoscale Devices
2:00–2:15	*Sabrina Feldman*—NASA Ames Research Center Next-Generation XRD Requirement

2:15–2:30	*Brook Lakew*—NASA Goddard Space Flight Center IR Sensors and Planetary Missions
2:30–2:45	*David Bartine*—NASA Kennedy Space Center Next-Generation Shuttle Sensors
2:45–3:00	Group Discussion
3:00–3:15	Coffee Break

Wrap-Up Overview (Chair: Harry Partridge)

3:15–3:30	*Calvin Shipbaugh*—Rand Corporation Defense and Security
3:30–3:45	*Sean Casey*—Universities Space Research Association Session Wrap-up
3:45–4:45	Group Discussion
5:00	End of Session

6. ASTRONAUT HEALTH MANAGEMENT (Foster Room)

August 24, 2004

Nanomedicine

1:30–2:00	*Jack Smith*—NASA Johnson Space Center Health Care Systems for Exploration
2:00–2:30	*James F. Leary*—University of Texas Medical Branch Engineering Nanosystems for Nanomedicine for Continuous Astronaut Health Monitoring in Space
2:30–3:00	*Shuvo Roy*—Cleveland Clinical Foundation Nanomedicine at the Cleveland Clinic
3:00–3:30	*CDR Wayne Horn*—Navy Submarine Medical Research Lab Astronaut Health: A View from Submarine Medicine
3:30–5:00	Discussion

August 25, 2004

Nanodiagnosis/Nanotreatment

8:30–8:50	*David Goodsell*—The Scripps Research Institute Prospects of Bionanotechnology in Health Management
8:50–9:10	*Susan Hardin*—VisiGen Biotechnologies, Inc. Real-time DNA Sequencing

9:10–9:30	*Tammy Oreskov*—National Institute of Standards and Technology Cell Viability in Contact with Carbon Nanotubes
9:30–9:50	*Ananth Annapragada*—University of Texas Health Sciences Center Nanotechnology Approaches to Space Medicine
9:50–10:10	*Jun Li*—NASA Ames Research Center Ultra-Sensitive Label-Free Electronic Chips for DNA/RNA Analysis Based on Carbon Nanotube
10:10–10:30	*Katrin Kneipp*—Harvard Medical School Single Molecule and Nanoscale Spectroscopy Potentials and Capabilities in Life Sciences
10:30–10:50	*Louis Brousseau*—Quantum Logic Devices Nanoelectronic “Digital Detection” of Biomarkers for Simple, Rapid, Palm-top Health Monitoring
10:50–12:00	Discussion
1:30–1:50	*Mark Kliss*—NASA Ames Research Center Advanced Life Support Research and Technology Development Efforts for Exploration Mission
1:50–2:10	*Neva Çiftçioğlu*—Universities Space Research Association Self-Replicating Biogenic Apatite Particles, “Nanobacteria,” and Their Potential Impact on Space Crew Health
2:10–2:30	*R. Kelley Bradley*—Universities Space Research Association, NASA Johnson Research Center
2:30–2:50	*Mary Tang*—Stanford Nanofabrication Facility Stanford Nanofabrication Facility: The Ultimate Sandbox for BIOMEMS and Bioengineering R&D
3:00–5:00	Discussion

APPENDIX B. WORKSHOP PARTICIPANTS AND CONTRIBUTORS[†]

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Nanomaterials Session

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Appendix C. Glossary

A

AFM	Atomic force microscopy
ARC	Ames Research Center (NASA)
ATP	Adenosine triphosphate
AVT	Agglomerated vesicle technology

C

CEV	Crew Exploration Vehicle (NASA)
CNT	Carbon nanotube
CT	Computer tomography
CW	Continuous wave

D

DARPA	Defense Advanced Research Projects Agency (DOD)
DOD	Department of Defense
DOE	Department of Energy

E

EVA	Extra-vehicular activity

F

FFM	Frictional force microscopy

G

GSFC	Goddard Space Flight Center (NASA)

I

ISHM	Integrated system health management

J

JPL	Jet Propulsion Laboratory (NASA)

M

MBE	Molecular beam epitaxy
MEMS	Microelectromechanical systems
MMOD	Micrometeors and orbital debris
MWCNT	Multiwalled CNT

N

NASA	National Aeronautics and Space Administration
NB	Nanobacteria
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NMR	Nuclear magnetic resonance
NNCO	National Nanotechnology Coordination Office
NNI	National Nanotechnology Initiative
NSET	Nanoscale Science, Engineering, and Technology Subcommittee of the NSTC
NSF	National Science Foundation
NSTC	National Science and Technology Council

O

OSTP	Office of Science and Technology Policy (Executive Office of the President)

P

PICA	Phenolic impregnated carbon ablator

Q

QD	Quantum dot
QDIP	Quantum dot infrared photodetector

R

RAD	Renal assist device
RF	Radio frequency
RF-SET	Radio frequency single-electron transistor
RH	Relative humidity

S

SEC	Size-exclusion chromatography
SERS	Surface-enhanced Raman scattering (spectroscopy)
SET	Single-electron transistor
SiCNT	Silicon carbide nanotube
SPL	Scanning probe lithography
SPM	Scanning probe microscopy
STM	Scanning tunneling microscopy
STS	Space Transportation System (NASA, otherwise known as the Space Shuttle)
SWCNT	Single-walled carbon nanotube

T

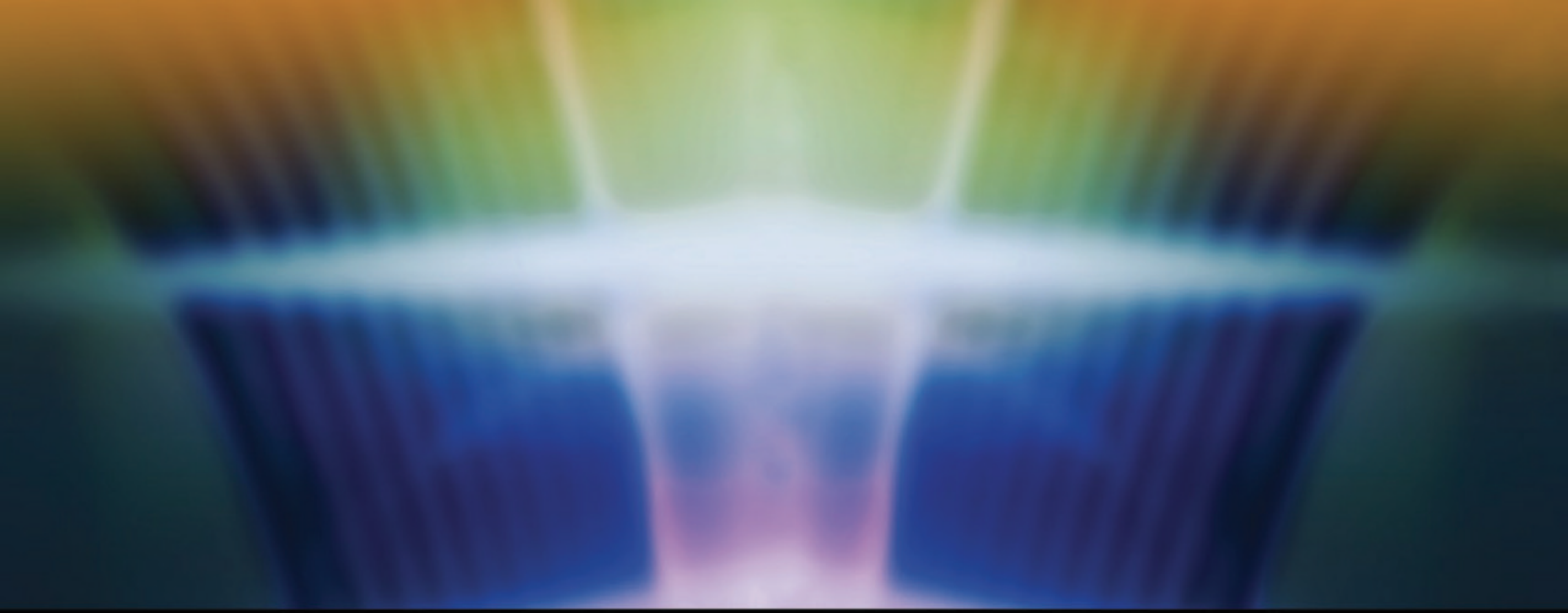
TEM	Transmission electron microscopy
TMT	Technology maturation team
TPS	Thermal protective system
TRIPS	Thermal, radiation, and impact protective shields
TRL	Technology readiness level

U

UAV	Unmanned aerial vehicle
UGV	Unmanned ground vehicle
URETI	University Research Education Technology Institute (NASA program)
UUV	Unmanned underwater vehicle

X

XRD	X-ray diffraction
XRF	X-ray fluorescence



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