Nanotechnology Presentation Agenda
7:30  Continental Breakfast
8:00  Welcome and Review Process, Panel Chair & NRC Staff
8:15  Introduction by APIO to NASA Capability Roadmapping  Julie Crooke
8:50  Nanotechnology Presentation Agenda  Murray Hirschbein, NASA
9:00  Background: Nanotechnology at NASA  Minoo Dastoor, NASA
9:45 - 10:15  – Break –
10:15  Overview and Summaries of Roadmapping Activity  Minoo Dastoor, NASA
10:45  Nano-Structured Materials  Ilhan Aksay, Princeton
       (Mike Meador and Len Yowell, NASA)
11:15  Sensors and Devices  David Janes, Purdue
       (Harry Partridge, NASA)
11:45 - 12:45  – Lunch –
12:45  Intelligent/Integrated Systems  Chih-Minh Ho, UCLA
       (Benny Toomarian, JPL)
1:15   Summary and Next Steps  Minoo Dastoor
1:30   Closure and Crosswalk (with other Roadmaps)  Murray Hirschbein
2:00   Open Discussion
3:30   – Break/NRC Panel Closed Session –
4:15   NRC Panel Discussion with NASA
5:00   Adjourn
Background: Nanotechnology at NASA
Background: Nanotechnology at NASA

Presentation to the National Research Council

March 8, 2005
Washington, D.C.

Co-Chairs:
M. Dastoor (NASA HQ)  M. Hirschbein (NASA HQ)  D. Lagoudas (Texas A&M)
Working at the atomic, molecular and supramolecular levels, in the length scale of approximately 1 – 100 nm range, in order to understand, create and use materials, devices and systems with fundamentally new properties and functions because of their small structure.

- NNI definition encourages new contributions that were not possible before.
  - novel phenomena, properties and functions at nanoscale, which are nonscalable outside of the nm domain
  - the ability to measure / control / manipulate matter at the nanoscale in order to change those properties and functions
  - integration along length scales, and fields of application
Revolutionary Technologies and Products

Fundamental research at the nanoscale

Knowledge Creation: same principles, phenomena, tools
Basic discoveries and new areas of relevance

Converging Technologies
Grand Challenges
Infrastructure Workforce Partnerships

-- Draft --
• Enable human and robotic exploration
**Personal Biomedical Monitoring**
- Identification of molecular indicators for onset of conditions
- High sensitivity assays
- Short prep-time assays, no prep-time assays and in vivo monitoring
- Multiple simultaneous assays

**Personal Countermeasures**
- Timed drug release
- Targeted drug therapy
- Triggered drug release
- Indicators for drugs effectiveness

**Major Medical Operations**
- Contrast agents to target specific sites for surgery
- Bio-mimetic or engineered compounds to help wound healing
- Miniaturized electron microscopes for biopsies

**Life Support**
- High surface area materials for CO₂ removal
- Inorganic coatings that catalyze the revitalization of air and water
- Sensors to monitor harmful vapor and gases

**Basic Biomedical Research**
- The role that forces plays on cell mechanisms (gravitational forces)
- Molecular machines (ATPase, Kinesin, Microtubules, Polymerase, etc.)
- In vivo monitoring of ultra-low concentration proteins and biomolecules

**Toxicology & Ethics**
- Biodistribution of nanoparticles
- Toxicology of nanoparticles
- Ethical use of information from nanotech devices

**Systems Integration**
- Develop ‘common toolkit’ for bio-nano chemistry and assembly processes
Capability Roadmap: Nanotechnology
Mars Exploration Pathway - Next Decade

2011
2013
2016
2018
2020

- Draft -
### Dynamic Space and Earth Science Events

<table>
<thead>
<tr>
<th>Vantage Points</th>
<th>Capabilities</th>
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<tbody>
<tr>
<td>Fan-Space</td>
<td>UL1/2, HEO/GO: Sentinel satellites for continuous monitoring</td>
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<tr>
<td>Near-Space</td>
<td>LEO/MEO: Active &amp; passive sensors for trend &amp; process studies</td>
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<tr>
<td>Airborne</td>
<td>Suborbital: In situ measurement &amp; validation of new &amp; remote sensors</td>
</tr>
<tr>
<td>Terrestrial</td>
<td>Deployable: Ocean buoys, air samplers, strain detectors, ground validation sites</td>
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</tbody>
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#### The Bigger Picture...
- Gamma Ray Burst
- Mars Dust Devils
- In Lava Flow
- Hurricane
- Volcanic Ash Plume

#### Dynamic Space and Earth Science Events

- **Space**
- **Airborne/Suborbital**
- **Surface/Subsurface**
Hydrogen fuel, electric propulsion – zero environmental impact

High Altitude and Long Endurance (HALE) for...

Science and....

“Perpetual Flight”

Clean and Quiet Aircraft

• Light Weight
• High Strength
• High Reliability
• High Efficiency

About the Earth and Other Planets
• Performance in Extreme Environments (Radiation, Temperature, Zero Gravity, Vacuum)
• Light Weight
• Frugal Power Availability (for Space Systems)
• High Degree of Autonomy and Reliability
• Human “Agents” and “Amplifiers”
• New and Powerful computing technologies
  • Onboard computing systems for future autonomous intelligent vehicles; powerful, compact, low power consumption, radiation hard
  • High performance computing (Tera- and Peta-flops)
    - processing satellite data
    - integrated space vehicle design tools
    - climate modeling

• Smart, compact devices and sensors
  • Ultimate sensitivity to analytes
  • Discrimination against varying and unknown backgrounds
  • Ultrasmall probes for harsh environments
  • Advanced miniaturization of all systems

• Microspacecraft/Micro-Nanorovers
  • “Thinking” Spacecraft with nanoelectronics/nanosensors
  • Size reduction through multifunctional, smart nanomaterials
High Impact Application Areas for Nanotechnology: Exploration Missions

- **Advanced Materials**
  - High strength-to-weight composites for vehicle primary structures and habitats
  - Hydrogen resistant nanostructured materials for cryotanks
  - High thermal conductivity materials for heat sinks, heat pipes, and radiators
  - High temperature materials for propulsion systems and thermal protection systems
  - High electrical conductivity materials for wiring
  - Self-healing materials for repairing impact damage and wire insulation
  - Space-durable materials resistant to ultraviolet and particle radiation
  - Self-assembling materials for in-space fabrication

- **Power**
  - High energy density batteries and fuel cells
  - High efficiency photovoltaic cells

- **Sensing**
  - Bio-chemical sensors for monitoring environmental contaminants in crew habitats
  - Bio-chemical sensors for detecting the signatures of life on other planets
  - Chemical systems for identifying, processing, and utilizing planetary resources

- **Integral Health Management**
  - Systems that incorporate integral sensors and processors for fault detection and diagnosis

- **High Performance Computing**
  - Fault-tolerant reconfigurable processors, micro-controllers, and storage devices

- **Extreme Environment Electronics**
  - Microelectronic devices that can operate reliably in extreme temperature and radiation environments
High Impact Application Areas for Nanotechnology: Science Missions

- Propulsion & Hydrogen Storage
- Low Areal Density Structures
- Power Generation & Energy Storage
- Large Apertures
- Precision Structures
- Thermal Management Radiation Shielding
- Sensors, Information Processing & Communication
Nanostructured Materials
- High strength/mass, smart materials for aerospace vehicles and large space structures
- Materials with programmable optical/thermal/mechanical/other properties
- Materials for high-efficiency energy conversion and for low temperature coolers
- Materials with embedded sensing/compensating systems for reliability and safety

Nano Electronics and Computing
- Devices for ultra high-capability, low-power computing & communication systems
- Space qualified data storage
- Novel IT architecture for fault and radiation tolerance
- Bio-inspired adaptable, self-healing systems for extended missions

Sensors and Microspacecraft Components
- Low-power, integrable nano devices for miniature space systems
- Quantum devices and systems for ultrasensitive detection, analysis and communication
- NEMS flight system @ 1µW
- Bio-geo-chem lab-on-a-chip for in situ science and life detection

University Research Engineering and Technology Institutes
- Bio-nano-information technology fusion (UCLA)
- Bio-nanotechnology materials and structures (Princeton)
- Bio-nanotechnology materials and structures (Texas A&M)
- Nanoelectronics computing (Purdue)
Bio-Inspired Design and Processing of Multi-Functional Nano-Composites (BIMat)

- Design and modeling of hierarchically structured materials capable of bio-sensing catalysis and self-healing

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<thead>
<tr>
<th>Princeton</th>
<th>Northwestern</th>
<th>Nat’l Inst. Aerospace</th>
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<tr>
<td>UCSB</td>
<td>U of NC</td>
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Institute for Nanoelectronics and Computing (INAC)

- Develop fundamental knowledge and enabling technologies in: ultradense memory, ultraperformance devices, integrated sensors, and adaptive systems

<table>
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<th>Purdue</th>
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<th>Cornell</th>
<th>Texas A&amp;M</th>
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<td>Yale</td>
<td>U of FL</td>
<td>UCSD</td>
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Institute for Intelligent Bio-Nano Materials and Structures for Aerospace Vehicles (TiiMS)

- Basic and applied research in: the integration of sensing, computing, actuation and communication in smart materials

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<th>Texas A&amp;M</th>
<th>Texas Southern</th>
<th>U of T-A</th>
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<tr>
<td>Rice</td>
<td>Prairie View A&amp;M</td>
<td>U of Houston</td>
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Center for Cell Mimetic Space Exploration (CMISE)

- Bio-informatics for the development of new, scalable nano-technologies in sensors, actuators and energy sources

<table>
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<th>UCLA</th>
<th>Ariz. St</th>
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<td>CIT</td>
<td>UCI</td>
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</table>
Capability Roadmap: Nanotechnology
Electron Sources - Application Regimes

- Electron Beam-pumped UV Laser Source
- Nanoklystron
- High current density electron field emission source
- Miniature Mass Spectrometer
- Miniature X-ray Diffraction Fluorescence Spectrometer (David Blake, Ames Res Center)
Present Phase

- Production of Nanomaterials
- Characterization at Atomic/Bulk Scale
- Nanoscale Modeling and Simulation

Next Phase

- Integration of “Nanoworld” with the “Macroworld”
- Integration of Wet World with Dry World
- Emergence of Intelligence from Complexity
- Multi-scale Modeling and Simulation Hierarchy
• **Science at the nanoscale**
  - The Physics of the behavior of molecules/atoms at the mesoscale is poorly understood. The full potential of nanotechnology will be realized when such “new” laws are established.

• **Production of nanomaterials**
  - Quantity, quality, control of properties & production in specified forms

• **Characterization at both atomic and bulk scale**
  - Fundamental mechanical, electrical and optical properties

• **Modeling & Simulation**
  - Prediction of physical/chemical properties and behavior from nanoscale to macroscale as well as models for material production
Backup
Radiation Dose (Mega-Rads)

3.2 Mrad
Over 1-2 years in Jupiter orbit before Europa Landing

3.3 Mrad
During a 30-day Period In Europa orbit

SRO: Science Relay Orbiter

Current Missions: Iridium, Intelsat, Galileo

Planned Missions: Europa Orbiter (X2000), Galileo, Intelsat

MEO Telecom Sats: 10 year duration, 10-12 year duration

7 year duration

1 year duration
X-Aerogels Have Potential as Structural Materials

Versatile Cross-linking Chemistry

Tailorable Properties

400 Fold Increase in Strength

Simplified (Ambient Pressure) Processing, Improved Machinability
• Modified Ames process for high/engineered surface area
• Characterization of SWCNT material:
  • BET – Quantitative surface area + pore size
  • SEM – Qualitative surface area characteristics

• **Initial Performance Test:**
  – Solid amine coating: University of Connecticut
  – **Thermogravimetric Equilibrium Experiment**
    • Pressure Swing
    • Temperature Swing

• **Reduce system volume**
• **Increase efficiency**
• **DoE Smokestack application**
Nano-imprinted Crossbar Arrays

60 nm half-pitch

1 mm
100 μm
10 μm
1 μm
100 nm

Courtesy of Stan Williams, Hewlett-Packard
• September 2004 Workshop on Micro-Spacecraft and Robotics
  • NASA-led National Nanotechnology Initiative Grand Challenge area
  • Expanded scope covered elements of President’s Exploration Vision
    • Nano-materials
    • Nano-Sensors and Instruments
    • Nano-Robotics
    • Nano-Micro-Macro Integration
    • Microcraft
    • Astronaut Health Management
Capability Roadmap: Nanotechnology

Charge To Workshop Breakout Sessions

Executive Summary:
- Goals
- Value
- Hard Problems
- SOA

Nano-Micro-Macro Integration
- Electronics
- Sensors / Instrumentation
- Actuators
- New algorithms
- Communications

Nano-Micro-Macro Integration
- Microcraft
  - Deep Space Probes
  - Orbiters
  - Planetary Entry / Surface Probes
  - Micro/Nano/Pico-craft

Nanomaterials
- Structural
- Power / Energy Storage
- Thermal Management
- Shielding
- Multifunctionality

Nanorobotics
- Actuation and Control
- Molecular Actuation
- Micromachines

Nanosensors and Instrumentation
- Biological
- Chemical
- Radiological
- System / Vehicle Health
- In-situ Analysis

Astronaut Health Management
- Personal Biomedical Monitoring
- Personal Countermeasures
- Basic Biomedical Research
- Major Medical Operations
- Life Support

– Draft –
## Capability Roadmap: Nanotechnology

### Microcraft & Constellations Summary

<table>
<thead>
<tr>
<th>Goals</th>
<th>Hard Problems</th>
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| • Reduce mass of microcraft by factor of ~100 in 10 years and ~1000 in 20 years, while maintaining full functional capability at no increase in cost/kg  
• Fly "Constellations" of 100s-1000s microcraft and enable them to managed by a few (maybe only one) human operators | • Systems-level design and integration of nanotechnology into single microcraft and constellations for ≥ 10X performance over SOA: power, propulsion, communications, computing, sensing, thermal control, guidance/navigation, etc.  
• Assuring durability and endurance, especially in harsh environments  
• Increase on-board computational performance by ~100X for self-directed, intelligent operations |

<table>
<thead>
<tr>
<th>Value to Space Systems</th>
<th>State of the Art</th>
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</table>
| • Much greater capability at much lower cost  
• Distributed robust monitoring and inspection for safer operations  
• Simultaneous dense sampling of phenomena for exploration and accurate modeling of Earth, planetary, and space environments | • Commercial satellites (e.g. Orbcom) @ 40Kg  
• Sojourner Mars Rover @ 11.5 kg  
• "Picosats" (some MEMS) 0.27 to 1 Kg flown on expendable and STS vehicles  
• Variety of lab prototype vehicles at 10-100 g, all with sensing, computation, communications, and actuation |
## Astronaut Health Management Summary

### Goals
- To provide medical care (prevent, diagnose, and treat) during long-term transportation and extended presence in Moon and Mars
- The rapid development in the field of nanotechnology and biotechnology will provide significant solutions in the Astronaut Health Management arena during the long-term manned mission to Moon and Mars

### Hard Problems
- Biocompatibility, especially toxicity of the nano-derived systems with the humans
- Management of the large volume of data and timely analysis of the data for medical assessment and subsequent treatment
- Integration of different disciplines from product development to clinical maturation
- Requirement for instrumentation autonomy while maintaining reliability

### Value to Space Systems
- Screening for Personnel for minimal risk (radiation susceptibility, genetically high risk)
- Monitoring and countermeasure (radiation, bone loss, immune, muscle...)
- Autonomous Medical Care (Non-invasive Diagnostics, non-invasive imaging and Therapeutics, blood replacement therapy)
- Atmosphere monitoring and control (Environmental parameters, contaminants)
- Human Factors (Early assessment of performance quality)
- Antimicrobial coatings, High capacity regenerative adsorbants, Food packaging

### State of the Art
**In Shuttle and ISS**
- Hearing test – EarQ
- Monitoring Heart Rate and Oxygen Consumption during exercise work load.
- Assess neurocognitive function (short term memory, verbal memory, math skills)
- Portable Clinical Blood Gas Analyzer – iStat (measures pH, blood gas, glucose...)
- Intra-vehicle radiation monitor to track crew exposure
- Ultrasound for research purposes only
Overview and Summaries of Roadmapping Activity
Overview:
Nanotechnology Capability Roadmap

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Co-Chairs:
M. Dastoor (NASA HQ)  M. Hirschbein (NASA HQ)  D. Lagoudas (Texas A&M)
• Capability Roadmap Team
• Capability Breakdown Structure
• Roadmap Approach
• Top Level Assumptions
• Top Level Mission Sets
• Roadmap Schedule
• Capability Presentations by Leads under Roadmap (Repeated for each capability under roadmap)
  – Capability Description, Benefits, Current State-of-the-Art
  – Capability Requirements and Assumptions
  – Roadmap for Capability
  – Maturity Level - Technologies
  – Metrics
• Summaries of Top Level Capabilities
Co-Chairs
NASA: Murray Hirschbein (Headquarters)
NASA: Minoo Dastoor, (Headquarters)
External: Dimitris Lagoudas, (Texas A&M, URETI Director*)

Government (NASA/JPL)
Mike Meador (Glenn Research Center)
Harry Partridge (Ames Research Center)
Mia Siochi/Mike Smith (Langley Research Center)
Benny Toomarian (Jet Propulsion Laboratory)
Len Yowell (Johnson Space Center)

Academia
Wade Adams (Rice, Center for Nanoscale S&T)
Ilhan Aksay (Princeton, URETI* Director)
Supriyo Datta/David Janes (Purdue, URETI* Director)
Chih-Ming Ho (UCLA, URETI* Director)

Industry
Dan Herr, (SRC)
John Starkovich, (Northrop-Grumman)
Stan Williams (Hewlitt-Packard)

Coordinators
Directorate: Harley Thronson (Science)
APIO: Julie Crooke (GSFC)

* University Research Engineering and Technology Institute
16.0 Nanotechnology

16.1 Nano-structured Materials
- External Lead: Ilhan Askay
- NASA Lead: Mike Meador
- Len Yowell
- 16.1.1 Structural Efficiency
- 16.1.2 Efficient Power and Energy
- 16.1.3 Thermal Protection and Management
- 16.1.4 Radiation and EM Protection
- 16.1.5 Life Support/Health Management
- 16.1.6 Sensing and Actuating

16.2 Sensors and Devices
- External Lead: David Janes
- NASA Lead: Harry Partridge
- 16.2.1 Sensing
- 16.2.2 Electronics
- 16.2.3 Mechanisms/Actuators
- 16.2.4 Modeling and Simulation

16.3 Intelligent Integrated Systems
- External Lead: Chih-Ming Ho
- NASA Lead: Benny Toomerian
- 16.3.1 Multi-Scale Modeling
- 16.3.2 Multi-Scale Manufacturing
- 16.3.3 Interconnectivity
- 16.3.4 Utilization of Nano-Scale Properties
- 16.3.5 Information Representation
Roadmap Approach

• **Build on 5+ years of similar activity including prior roadmaps and involvement in the National Nanotechnology Initiative (NNI)**
  - Recent planning for the second 5 years of NNI
  - NASA NNI workshop Microcraft and Robotics
  - Recent workshop among the four NASA University, Research, Engineering and Technology Institutes in nanotechnology (URETI)
  - Utilize existing informal NASA team, including URETIs, that has evolved over the past several years

• **The scope will include both aeronautics and space**
  - Both near and mid-term opportunities and long-term vision
  - Tie development of capability to enabling higher level applications
  - Key demonstrations and quantifiable milestones to gauge progress

• **Focus on fundamental underlying technological capability, such as**
  - Theory and analysis from the nano-scale to the macro-scale to predict properties and behavior
  - Materials processing for desired properties and behavior
  - Design and development of devices and systems based on nano-scale technology
  - Integration of nano-scale devices and systems into micro- to macro- systems
  - Training and Education
• Continue active participation in the National Nanotechnology Initiative to enhance broad government coordination and cooperation

• NASA will work closely with....
  • NIH in matters of astronaut health
  • DOD across broad common interests in aeronautics and space
  • DOE in materials, especially energy related
  • NIST on fabrication and manufacturing (NASA fabricates, but does not manufacture)
  • Semiconductor industry (ITRS) for electronics and system integration
Top Level Assumptions

- Nanotechnology is a “push” technology driven by breakthroughs and opportunities
  - No mission currently “requires” nano-scale technology
  - All planned and future missions can significantly benefit from advances in nano-scale technology
- The most significant breakthroughs in nano-scale technology likely have not yet occurred – predictions beyond a few years are very speculative
- Most advances benefiting NASA will come from external sources
- The target level for the nanotechnology roadmap is about Technology Readiness Level 4 (fully demonstrate/validate functionality)
- Leveraging Commercial/Academia developments is essential
- NASA will have unique needs and requirements not met by external sources
- A strong internal emphasis and highly competent internal talent is essential to benefit from external sources and satisfy unique needs and requirements
Mission Needs/Opportunity Timeline for Nanotechnology

1st Generation:
- Power Generation/Storage, Life Support, Astronaut Health Mgt, Thermal Mgt.
- High Strength, Lt. Wt./ Multifunctional Structures

1st Generation Zero Emissions Aircraft

High Altitude Long Endurance Aircraft

Robotic Missions to Extreme Environments After Mars (Outer Solar System, Venus …)

Mars Transfer Vehicle

Lightweight Fuel Tanks, Radiators (Nuclear Prop.)

Humans to the Moon

Radiation Protection, Advanced TPS

Humans to Mars

High Strength/ Multifunctional Structures

Large, lightweight highly stable optical and RF apertures and metering structures (~10m)

Lunar and Mars Robotics Precursor

Deep Space Constellations (X-Ray Telescope, Earth's Magnetosphere, …)

Thermal control; lightweight, low power radiation hard/tolerant electronics and avionics; advanced active/detection; lightweight high efficiency power systems; high strength-to-weight structures and thermal protection systems


2nd Generation
- Power Generation/Storage, Life Support, Astronaut Health Mgt, Thermal Mgt.
- High Strength/ Multifunctional Structures

Lt. Weight High Strength Structures

Lightweight Fuel Tanks, Radiators (Nuclear Prop.)

“Planetary Aircraft” (e.g. Mars)

Very Long Baseline Interferometry (Planetary Imaging)

Large Scale Interferometry (Planetary Finding)

Deep Space Constellations (X-Ray Telescope, Earth's Magnetosphere, …)

Humans to Mars

Extremely large, lightweight, highly stable optical and RF apertures and metering structures (~10-100 m)

Greatly miniaturized robotic systems: 1 kg-sats/robots with the capability of today’s 100 kg systems (Mars and other planetary bodies: in orbit, atmospheres, surfaces, sub-surfaces)

Mars robotic missions (every 2 years)

Large Scale Interferometry (Planetary Finding)

Sun-Earth Observing Constellations

Deep Space Constellations (X-Ray Telescope, Earth’s Magnetosphere, …)

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Roadmap Schedule

• Team established in November

• First team meeting December 14-15, 2004
  - External perspectives
  - Organized sub-teams
  - Focused on what should NASA do in nanotechnology and why

• Second team meeting February 1-2, 2005
  - Developed final capability breakdown structure
  - Focused on how and when NASA could achieve Agency needs/benefits in nanotechnology
  - Initial draft of roadmaps including state-of-the-art, metrics and timelines
Roadmap Schedule (continued)

• NRC review March 8, 2005
  - Integral part of nanotechnology roadmapping plan
  - “Mid-term” assessment of assumptions, scope, direction and overall technical content
  - Early enough in the process to affect final product

• Third meeting in March
  - Incorporate NRC feedback
  - Finalize content
Nano-Structured Materials
Capability 16.1 Nanostructured Materials

Presenter/Team Lead:
Ilhan Aksay

Co-Leads:
Mike Meador-GRC
Leonard Yowell – JSC

Team Members:
Wade Adams – Rice University
Mike Smith - LaRC
John Starkovich – Northrop Grumman
• Nanotechnology is producing materials with properties, processing and durability far exceeding that of conventional materials. These materials will have a significant, pervasive impact on all NASA missions:
  – Reduced mass, improved structural efficiency
  – Extreme environmental performance
  – Efficient power (frugal consumption, efficient generation, storage and management)
  – High reliability
  – Human safety
• Critical drivers for all NASA Missions:
  – Weight
  – Performance
  – Power and Energy
  – Safety
• Benefits and improvements identified by theoretical and laboratory based experimental results are achievable at scales required for NASA missions
• TRL 4 includes scale-up to appropriate size/quantity
• Resources will be available to develop technologies to TRL4
• Nanotechnology Roadmap assumes that technology will be developed to TRL4, other CBS and WBS Roadmaps will:
  – Identify opportunities for insertion of nanotechnology
  – Develop roadmaps for insertion and maturation to higher TRLs
<table>
<thead>
<tr>
<th>Benefit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical</strong></td>
<td></td>
</tr>
<tr>
<td>Strength</td>
<td>nano length scales below Griffith criteria</td>
</tr>
<tr>
<td>Toughness</td>
<td>distributed deformation at nanolength scales</td>
</tr>
<tr>
<td>Damping</td>
<td>efficient energy dissipation at nano-interfaces, nanomorphology, increased viscoelasticity with nanoparticle addition</td>
</tr>
<tr>
<td>Hardness</td>
<td>supermodulus effect - nanoscale inclusions</td>
</tr>
<tr>
<td>Modulus/Stiffness</td>
<td>enhanced molecular alignment - more perfect structures - achieve theoretical limits</td>
</tr>
<tr>
<td>Recoverable strain</td>
<td>quantum level nanoeffects</td>
</tr>
<tr>
<td>Compressive</td>
<td>toughened interfaces through nanoscale particles, nanovoids</td>
</tr>
<tr>
<td>Impact/Dynamic Loading</td>
<td>nanomorphology effects on energy dissipation</td>
</tr>
<tr>
<td>Friction and Wear</td>
<td>tailored nanostructures to fit asperities</td>
</tr>
<tr>
<td><strong>Thermal</strong></td>
<td></td>
</tr>
<tr>
<td>Conductivity/Insulation</td>
<td>geometry and size effects at a wide range of temperatures (cryo to reentry)</td>
</tr>
<tr>
<td>CTE</td>
<td>nanoscale morphology (voids) effects, phonon coupling, enables tailorable CTE</td>
</tr>
<tr>
<td>Emissivity</td>
<td>enhanced surface area/roughness, possible quantum effect</td>
</tr>
</tbody>
</table>
## Benefits of 16.1 Nanostructured Materials

### Why Nanotechnology

<table>
<thead>
<tr>
<th>Property</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrical</strong></td>
<td></td>
</tr>
<tr>
<td>DC Conductivity</td>
<td>nanoscale design/defects, enables ballistic conductivity</td>
</tr>
<tr>
<td>Semiconductive</td>
<td>nanoscale tailoring of bandgaps</td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td>nanopores</td>
</tr>
<tr>
<td>Current Density</td>
<td>enables ultra-high current densities, eliminates/controls defects, size</td>
</tr>
<tr>
<td></td>
<td>effects, gating of nanowires</td>
</tr>
<tr>
<td>Percolation Threshold</td>
<td>high aspect ratios</td>
</tr>
<tr>
<td>Field emission</td>
<td>high aspect ratio</td>
</tr>
<tr>
<td>Thermoelectric</td>
<td>larger density of states, more phonon scattering</td>
</tr>
<tr>
<td><strong>Optical</strong></td>
<td></td>
</tr>
<tr>
<td>Transparency</td>
<td>size effects (clearly)</td>
</tr>
<tr>
<td>Color/Absorption</td>
<td>size effects</td>
</tr>
<tr>
<td>Photonic Band Gap</td>
<td>tailored bandgaps through nanostructures, size effects (lambda/10)</td>
</tr>
<tr>
<td>Left-Handed</td>
<td>size effects</td>
</tr>
<tr>
<td>Surface Area</td>
<td>size, radius of curvature and geometry effects, tailorability</td>
</tr>
<tr>
<td>Porosity</td>
<td>hierarchical distribution, functionalization</td>
</tr>
</tbody>
</table>
### Benefits of 16.1 Nanostructured Materials

**Why Nanotechnology**

<table>
<thead>
<tr>
<th>Category</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Transport/Permeability</td>
<td>nanoscale morphology (voids) effects, length scale effects on diffusion mechanisms</td>
</tr>
<tr>
<td>Density</td>
<td>nanomorphology (inclusion of nanopores)</td>
</tr>
<tr>
<td>Environmental</td>
<td></td>
</tr>
<tr>
<td>Radiation</td>
<td>electronics (smaller cross-section, redundancy, spintronics), human (size effects on energy dissipation?, design flexibility)</td>
</tr>
<tr>
<td>Temperature</td>
<td>nanoscale morphology (new interfaces), inhibits degradation (diffusion)</td>
</tr>
<tr>
<td>Stability/Performance</td>
<td></td>
</tr>
<tr>
<td>Corrosion</td>
<td>surface area, interface tailoring</td>
</tr>
<tr>
<td>Magnetic</td>
<td>size effect</td>
</tr>
<tr>
<td>Piezoelectric</td>
<td>size effect</td>
</tr>
<tr>
<td>Chemical Reactivity</td>
<td>surface area, interface tailoring</td>
</tr>
<tr>
<td>Materials Interactions</td>
<td>surface area and tailoring, interface tailoring</td>
</tr>
</tbody>
</table>
Future Exploration Missions Requirements Cannot Be Met with Conventional Materials

**Satellites and rovers**
- Reduced mass and volume
- Reduced power requirements
- Increased capability, multifunctionality

**Vehicles and habitats**
- Reduced mass
- High strength
- Thermal and radiation protection
- Self-healing, self-diagnostic
- Multifunctionality
- Improved durability
- Environmental resistance (dust, atmosphere, radiation)

**EVA Suits**
- Reduced mass
- Increased functionality and mobility
- Thermal and radiation protection
- Environmental resistance
Nanostructured Materials Can Impact Science Missions and Exploration

The Vision & The Challenges

- N^2 generation civil space missions require spacecraft and payload instruments with Order-of-Magnitude greater scale, resolution, and precision than present systems afford.
- Revolutionary designs and breakthrough technologies will enable development of such systems.
- NanoTechnology, particularly NanoEngineered materials may be key to realizing this vision.

- Very Large Simultaneous Reflectors
- Orbital Transfer Vehicles
- Large Deployable Structures
- Relocatable Power Beam Stations
- Dynamically Stable Platforms/Instruments
- Space-Based Radar & Constellations
Nanostructured Materials are Critical for Future Aeronautics Demonstrators

Zero Emissions Aircraft

- Airframe – ultralightweight, high strength, multifunctional nanocomposites
- Cryopropellant Tanks – low density, durable aerogel insulation & ultralow permeability nanocomposites
- Fuel Cell Power – nanostructured electrode materials
- Electric Motors – high conductivity, lightweight nanocomposites, nanolubricants
Key Assumptions: Potential NASA Applications

- **Structural Efficiency**
  - In-Space or In-Field Repair Methods
  - Composite Cryotanks
  - 20% Lighter Airframe and Propulsion Structures
  - Propulsion/Airframe Structures with 10X Life
  - 50% Lighter Composite Structures

- **Efficient Power and Energy**
  - EVA Suit and Rover Power
  - Power for UAVs
  - Exploration Systems Power Distribution, All-Electric Aircraft

- **Thermal Protection and Management**
  - Cryotank insulation
  - Insulation for EVA suits and rovers

- **Radiation and EM Protection**
  - Spacecraft Charging and Dust Mitigation
  - Multifunctional Materials for Vehicles, Habitats, Suits

- **Life Support/Health Mgt.**
  - Water Purification for Vehicles and Habitats
  - Astronaut Health Monitoring/Diagnostics
  - Air Revitalization for Vehicles, Habitats, EVA suits

Timeline:
- 2005
- 2010
- 2015

– Draft –
Capability Team 16.1: Nanostructured Materials

- Nanotube Based Microwave Repair
- Nanocomposite with 5000X lower permeability
- Nanotub supercapacitor with 5X power density
- Polymer Electrolyte with $10^{-4}\text{Scm}^{-1}\text{RT}$ conductivity
- Durable, rigid aerogel with densities <15mg/cc and thermal conductivities <10mW/mK
- Nanocomposites antistatic coatings
- Nanomaterial Water Filtration
- Quantum Dot Flow Cytometer for Astronaut Health Management
- Nanomaterial Fuel cell MEA with 50% higher power density
- Nanomaterial based Air Revitalization
- Ceramic Nanomaterial with 100X toughness
- 10 GPa Tensile Strength Nanotube Fiber
- Polyethylene-like radiation shielding capacity
- Multifunctional EMI/ESD structural nanocomposites
- High strength nanocomposite with polyethylene-like radiation shielding capacity
- Nanotube wires 10X conductivity of Copper
- Flexible aerogel with thermal conductivities <20mW/mK
- High strength nanocomposite with polyethylene-like radiation shielding capacity
- Nanomaterial Based Air Revitalization

- 16.1.1 Structural Efficiency
  - High Thermal Conductivity
  - Low Permeability, High Strength
  - Low Density, High Stiffness
  - Crack-Resistance, Ductility, Toughness
  - High Tensile Strength, Low Density

- 16.1.2 Efficient Power and Energy
  - High Electrical Conductivity
  - High RT ion conductivity
  - High electrical conductivity (electrodes), high proton conductivity (membrane)
  - Ballistic Conductivity

- 16.1.3 Thermal Protection and Management
  - Low density, high strength, low thermal conductivity
  - Flexible, ultralow density & thermal conductivity

- 16.1.4 Radiation and E&M Protection
  - High Conductivity, Low Density
  - Multifunctionality, Conductivity
  - Multifunctionality, Radiation Shielding

- 16.1.5 Life Support/Health Management
  - High Porosity, Chemical Selectivity
  - Biocompatibility, Bioselectivity

- 16.1.6 Sensing and Actuating (TBD)

2005 2010 2015

– Draft –
Key Assumption: Potential NASA Applications

- **Structural Efficiency**: 50% component weight savings, High temperature components with 100X longer life, Enables ultralightweight tethers
- **Efficient Power and Energy**: Lightweight Batteries for EVA Suits and Rovers, 50% Efficiency, Durable, Deployable PV Arrays
- **Thermal Protection and Management**: 50% Mass for TPS, Insulation, Reduced Mass, Efficient, Passive Thermal Control
- **Radiation and EM Protection**: Radiation Hard Electronics, Sensors, Advanced Radiation Shielding for Vehicles, Rovers, Habitats
- **Life Support/Health Mgt.**: Astronaut Health Monitoring/Countermeasures, Real-time, Multicomponent Astronaut Health Monitoring, Astronaut Health Care/Countermeasures

Timeline:
- 2020
- 2025
- 2030

– Draft –
Capability Team 16.1: Nanostructured Materials

16.1.1 Structural Efficiency
- High strength, low density polymer composite
- Improved durability, high strength ceramics
- High strength, lightweight fibers

16.1.2 Efficient Power and Energy
- High Spectral Absorption, Efficient Electron Transfer

16.1.3 Thermal Protection and Management
- Low Mass, Low Thermal Conductivity
- High Thermal Conductivity, Low Mass
- Low Mass, Highly Efficient Thermal Conductivity

16.1.4 Radiation and E&M Protection
- Radiation Protection/Resistance
- Efficient, Tailorable Radiation Protection

16.1.5 Life Support/Health Management
- Biocompatibility, Bioselectivity, Optical Absorption
- Biospecific Optical Properties, Biocompatibility
- Biocompatibility, Biospecificity

16.1.6 Sensing and Actuating (TBD)

- Draft -

- 2020
- 2025
- 2030
Remaining Work

• Review milestones and metrics for comprehensiveness
  – Fill in gaps – have we left out important needs?
  – Looking for expertise within and outside the Agency for validation of existing roadmaps and help with Sensing and Actuating Subcapability

• Coordinate Roadmaps with other CRM teams:
  – High Energy Power and Propulsion
  – Advanced Telescopes and Observatories,
  – Science Instruments and Sensors
  – Advanced Modeling, Simulation and Analysis
Detailed Challenges and Roadmaps
Grand Challenge: Develop the ability to reliably and consistently control functional material synthesis and assembly from nano to macro scales

Barriers/Needs:

- Integration of physical and chemical forces with external fields to get desired properties during processing and use (> 10 years)
- Inexpensive production (terrestrial and other planets) of highest quality nanomaterials (>10 years)
- Control of processes over all length scales (>10 years)
- Adaptable synthesis, processing and characterization methods to efficiently utilize resources on other planets (>10 years)
- Lack of fundamental understanding of synthesis, growth, nano-macro structure development mechanisms (5-10 years)
- Lack of real-time methods to characterize structural development during processing and/or synthesis (5-10 years)
- Lack of predictive models/simulations to guide materials and processing design (<5 years)
- Control of interfacial properties and processes (<5 years)
- Lack of approaches that draw upon previous experiences from other disciplines (bio, electrical engineering) (<5 years)
- Failure detection and prediction tools (<5 years)
- Lack of high throughput experimentation and characterization techniques (<5 years)
Grand Challenge: Demonstrate that materials, devices and systems based on nanotechnologies can reliably execute prolonged (DECADE +) Human and Robotic Exploration Missions.

- Radiation (space environment & propulsion radiation sources)
- Chemical/reactive environments
- Thermal swings (-120 C to 600 C)
- Fatigue
- MMOD Impact
- Mechanical and launch/entry loads
- Electrostatic charging
- Abrasion
- Synergistic effects.

Barriers/Needs:

- Accelerated life testing for issues listed above
- End-to-end test capability
- Lack of fundamental understanding of materials and interactions with radiation
- Simulation effects from Nano-micro-meso scale is imperative
- In Space repair and regeneration
- Integrated system health management
- Self-repair
16.1.1 Structural Efficiency

- **Includes:**
  - Low Density
  - Strength
  - Stiffness
  - Toughness
  - Vibration/Acoustic Damping
  - Permeability
  - Dimensional and Dynamic Stability
  - Environmental Durability
  - Impact Resistance
  - Self-Healing

- **SOA:**
  - Polymer/clay nanocomposites with 100X lower permeability than base resin
  - Nanocomposites with strength equivalent to conventional carbon fiber
  - Ceramic nanocomposites have toughness 10X that of best ceramic
  - Vibration damping - ?
  - Impact Resistance
  - Self-healing ionomers demonstrated that can heal 1 cm diameter cut, not space compatible
16.1.1 Structural Efficiency

• Metrics:
  – Nanocomposites with 5000X lower H2 permeability
  – Composite materials with 5-fold increase in specific strength and stiffness over conventional composites
  – Ceramic nanocomposites with 100 to 1000x better toughness
  – Vibration damping – (Will get information from Starkovich)
  – Impact resistance- Nanocomposite bumber and self-healing foam support to improve performance 10-100X
  – Nanotube based microwave active repair materials

• Barriers:
  – Lack of fundamental understanding of synthesis, growth, nano-macro structure development mechanisms
  – Reliable and affordable scale-up methods
  – Interface design, functionalization, control and characterization
  – Predictable structural control (dispersion and alignment) over all length scales
  – Lack of robust modeling tools across all length scales
  – In-situ characterization and diagnostic techniques are limited
Capability 16.1 Nanostructured Materials Roadmap

Key Assumptions:
- Potential NASA Application

In-Space or In-Field Repair Methods
- Composite Cryotanks
- 20% Lighter Airframe and Propulsion Structures
- Propulsion/Airframe Structures with 10X Life
- 50% Lighter Composite Structures

Nanotube Based Microwave Repair
- Nanocomposite with 5000X lower permeability
- Nanocomposite with 5X modulus
- Ceramic Nanomaterial with 100X toughness
- 10 GPa Tensile Strength Nanotube Fiber

16.1.1 Structural Efficiency
- Improved processing for dispersion
- Functionalization for enhanced dispersion
- Nanotube synthesis and purification
- Functionalization for improved interface
- Fiber spinning with enhanced alignment
- Improved Exfoliation (Processing and Functionalization)
- Understanding structure/permeability relationships
- In situ characterization of alignment during processing
- Improved interface (functionalization, processing)
- Improved alignment and dispersion
- In situ characterization of alignment/dispersion during processing
- Ceramic nanoparticle synthesis

2005 2010 2015

Draft
Key Assumptions: Potential NASA Applications

- 50% component weight savings
- High temperature components with 100X longer life

Capability Roadmap 16.1: Nanostructured Materials

- Nanocomposite with 5X Strength
- Ceramic nanomaterial with 1000X toughness
- 40-60GPa Tensile Strength Nanotube Fiber

16.1.1 Structural Efficiency

- Nanoparticle Purity
- Functionalization for Enhanced Interface
- Nanoparticle dispersion/alignment
- Controlled nanoparticle/ceramic interface
- Nanoparticle dispersion
- Directed Growth/Synthesis
- Functionalization for improved interface
- Fiber spinning techniques for enhanced alignment

2020
2025
2030
16.1.2 – Power and Energy Density

- Includes:
  - High Specific Power
  - High Specific Energy
  - Low Loss Power and Energy Distribution

- SOA:
  - Quantum dot/nanotube based photovoltaics with XX% efficiency
  - Nanotube double layer supercapitor with 5x power and 30x specific power of conventional supercapitors
  - Self-assembled polymer electrolyte with 10X ionic conductivity of conventional electrolyte at room temperature
  - Aerogel based membrane with Nafion-like conductivity but at 200°C and no need for external humidification
  - Wires??

- Metrics:
  - Material system capable of power generation, storage and self-actuation total aerial weight of 0.8Kg/m2 and capable of 1.0 kw/kg power generation
  - Solid polymer electrolytes with ionic conductivities >10-4 scm-1 at -70°C and structural capabilities
  - Multifunctional electrode materials for reversible fuel cells
  - Flexible, photovoltaic materials with 50% PV efficiency
  - Membranes?
  - Arm chair nanotube-based wires with 10X conductivity of copper at 1/6th the weight
Key Assumptions:
Potential NASA Applications

Capability Roadmap 16.1: Nanostructured Materials

Shuttle, ISS Power
EVA Suit and Rover Power
Power for UAVs
Exploration Systems Power Distribution, All-Electric Aircraft

16.1.2 Efficient Power and Energy
High Electrical Conductivity
High RT ionic conductivity
High electrical conductivity (electrodes), high proton conductivity (membrane)
Ballistic Conductivity

- Controlled nanotube synthesis and purification
- Functionalization for improved interface
- Chirality selective nanotube synthesis, purification
- Enhanced phase separation
- Understanding of structure/conductivity relationships
- Polymer and processing for optimized phase separation
- In situ characterization of phase separation during processing
- Nanotube based supercapacitor with 5X power density
- Polymer Electrolyte with $10^{-4}$ S cm$^{-1}$ conductivity at RT
- Nanomaterial fuel cell MEA with 50% higher power density
- Nanotube wires with 10X higher conductivity than Copper

2005 2010 2015

Draft
**Capability 16.1: Nanostructured Materials Roadmap**

**Key Assumptions:** Potential NASA Applications

- **Lightweight Batteries for EVA Suits and Rovers**
- **Improved Efficiency, Durable, Deployable PV Arrays**

**Capability Roadmap 16.1: Nanostructured Materials**

- **Solid Polymer Electolyte for -70°C Li-polymer Battery**
- **Flexible, Rad Hard Quantum Dot PV materials with 50% efficiency**

**16.1.2 Efficient Power and Energy**

- Polymer nanocomposites for enhanced ion mobility
- Processing, structure for optimum phase separation
- Controlled (size, chirality) nanoparticle synthesis
- Functionalization/interface control
- High ionic conductivity at -70°C
- High Spectral Absorption, Efficient Electron Transfer

**Timeline:**
- **2020**
- **2025**
- **2030**

- Ready to Use
- Major Decision
- Major Event / Accomplishment / Milestone

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**- Draft -**
16.1.3 – Thermal Protection & Management

• Includes:
  – Thermal Conductivity
  – Insulation
  – Emissivity

• SOA:
  – Flexible silica aerogel insulation with thermal conductivities below 20mW/mK
  – Zirconia/carbon nanotube TBC insulation with 50% lower thermal conductivity
  – Magnetically aligned nanotube ribbon conductors with metal-like thermal conductivities (200W/mK)
  – Emissivity

• Metrics:
  – Durable, aerogel insulation with densities below 15mg/cc and thermal conductivities below 10mW/mK
  – Nanotube ribbons with diamond-like thermal conductivities (1000-2000W/mK)
  – Emissivity?
Key Assumptions:
Potential NASA Applications

Cryotank insulation

Insulation for EVA suits and rovers

Capability Roadmap 16.1: Nanostructured Materials

Durable, rigid aerogel with densities <15mg/cc and thermal conductivities <10mW/mK

Flexible aerogel with thermal conductivities below 20mW/mK

16.1.3 Thermal Protection and Management

Low density, high strength, low thermal conductivity

Flexible, ultralow density & thermal conductivity

Nanotemplated coating development
Controlled nanoporous morphology

Aerogel & Nanocoating optimization

2005 2010 2015
**Capability 16.1 Nanostructured Materials Roadmap**

**Key Assumptions:**
Potential NASA Applications

**Reduced Vehicle Mass**
- Reduced Mass, Efficient, Passive Thermal Control

**Nanostructured Materials**

16.1.3 Thermal Protection and Management
- High Temp Nanomaterial TPS with 50% lower mass
- Nanotube Ribbons with Diamond-like Thermal Conductivity
- Bulk nanocomposite with thermal conductivities 2X that of diamond

**Nanoparticle Synthesis and Purification**
- Improved Interface
- Enhanced Dispersion
- Controlled nanotube synthesis and purification
- Controlled Alignment

**Thermal Conductivity**
- Low Mass, Low Thermal Conductivity
- High Thermal Conductivity, Low Mass
- Low Mass, Highly Efficient Thermal Conductivity

**Timeline:**
- 2020
- 2025
- 2030

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*Draft*
16.1.4 – Radiation Protection and E&M

- Includes:
  - Radiation Protection
  - EMI Shielding
  - Electrostatic Control
  - Active (Magnetic) Shielding

- SOA:
  - Nanotube based anti-static coatings
  - Polyethylene (non-nano) shielding

- Metrics:
  - Nanostructured materials with polyethylene-like radiation protection and structural capability
Key Assumptions:
Potential NASA Applications

Capability Roadmap 16.1: Nanostructured Materials

Spacecraft Charging and Dust Mitigation

Multifunctional Materials for Vehicles, Habitats, Suits

Nanocomposites anti-electrostatic coatings

Multifunctional EMI/ESD structural nanocomposites

High strength nanocomposite with polyethylene-like radiation shielding capacity

16.1.4 Radiation and E&M Protection

High Conductivity, Low Density

Multifunctionality, Conductivity

Multifunctionality, Radiation Shielding

Nanoparticle synthesis and purification

Processing and in situ process monitoring

Functionalization for enhanced dispersion

Functionalization for enhanced interface

Enhanced alignment during processing

Nanoparticle design for enhanced radiation protection

Understanding effects of structure on radiation protection capability

2005  2010  2015
Key Assumptions: Potential NASA Applications

Radiation Hard Electronics, Sensors

Advanced Radiation Shielding for Vehicles, Rovers, Habitats

Capability Roadmap 16.1: Nanostructured Materials

Nanocrystalline Materials for Rad Hard Electronics

Nanomaterial based active radiation protection

16.1.4 Radiation and E&M Protection

Radiation Protection/Resistance

Efficient, Tailorable Radiation Protection

Controlled growth and purity

In situ characterization/process monitoring

Functionalization for enhanced processing/manipulation

Controlled synthesis and purification for optimal electronic/magnetic properties

Functionalization for manipulation, alignment and interface

Modeling/understanding structure/electronic, magnetic property relationships

2020 2025 2030
16.1.5 – Life Support – Health Management

- Biocompatibility
- Selectivity (Separation and Filtration)
- Monitoring
- Counter-measures

• SOA:
  - Quantum dot bioassays for medical diagnostics/health monitoring
  - Functionalized nanotube membranes for water and air revitalization
  - Surface modified C60 antioxidants
  - Silica/metal nanoshells for diagnostics and photodynamic therapy and tissue welding

• Metrics:
Key Assumptions: Potential NASA Applications

2005

2010

2015
**Key Assumptions:**
Potential NASA Applications

**Astronaut Health Monitoring/Countermeasures**

**Real-time, Multicomponent Astronaut Health Monitoring**

**Astronaut Health Care/Countermeasures**

**Capability Roadmap 16.1: Nanostructured Materials**

- Nanoshells for Diagnostics and Photodynamic Therapy
- Nanomaterial Arrays for Multicomponent Bioassays for Astronaut Health
- Functionalized Nanomaterials for Cell Repair

**16.1.5 Life Support/Health Management**

- Biocompatibility, Bioselectivity, Optical Aborption
- Biospecific Optical Properties, Biocompatibility
- Biocompatibility, Biospecificity

**Nanomaterial Design and Modeling (Biocompatibility, Efficacy)**

- Functionalization for Biocompatibility, Photoactivity
- Nanomaterial Synthesis and Purification

- Quantum Dot Design, Functionalization
- Optical Properties and Bioselectivity

- Nanomaterial Design and Modeling (self assembly, self repair, biocompatibility)
- Controlled synthesis and purification
- Functionalization for biocompatibility and performance

**Timeline:**
- 2020
- 2025
- 2030
Capability 16: Nanotechnology

Capability 16.2 Sensing and Devices

Presenter/Team Lead:
David Janes
NASA Co-Leads:
Harry Partridge
• **Scope of Sensing and Devices**

  Provide the ability to detect, process data, communicate and interpret information, as well as manipulate or control this environment on a common platform by combining capabilities of nano/micro scale sensors and computing.

• **Why Nano Sensing and Devices?**
  
  – Unparalleled sensitivity, selectivity, multi-functionality and integration
  – Devices suitable for highly integrated systems
  – Considerable reduction in power consumption
  – Enabling multi-point monitoring and enhanced functionality from multi-node system (e.g., health management and microcraft)
  – Redundancy for fault-tolerance and elimination of false positives
  – Potential performance improvement in extreme environments (radiation, temperature (min/max & swings, pressure, zero gravity, etc.))
  – Bottom-up engineering of materials for device properties through independent control of physical parameters at nano-scale are becoming feasible.
Why NASA?

- Unique environment in space
  - radiation, temperature, micro-gravity, low power, resource limited
- Operation/Vehicle Safety
  - environmental management, systems status and health monitoring
- Astronaut health and environment monitoring and countermeasures
  - on-board and highly autonomous medical diagnosis and response capabilities with minimal resource requirement
- Unique measurements
  - Low photon counts, long wavelength, extreme temperatures and pressures, harsh chemical environment, detect biomarkers in remote environments
- Isolation from Earth
  - Need for low power, and high redundancy for increased autonomy because of communication delay
  - unique shelf life and reliability requirements for decades in radiation fields.
  - Materials with low outgas and devices with closely matched thermal expansion for thermal swings
- Intelligent, extremely small robotics systems for monitoring and science
  (NASA is the NNI lead agency for microcraft)
- Highly specialized and low volume manufacturing requirements not met by commercial development
Key Assumptions:

- Developments under National Nanotechnology Initiative, and other funded nanotechnology research, will continue to advance state of the art.
- Sensor community is very dynamic and will continue to develop new nano-scale technologies.
- Path available to transition from TRL 4 to mission insertion.
- Predictions of the state of nano-scale technology beyond about 2010 are highly speculative.
- Wireless technology available for integration of sensors and devices.
- Electronic device downscaling as per International Technology Roadmap for Semiconductors (ITRS).
Capability 16.2 CBS Sensing and Devices

Notional generic developmental profile for new nano-scale sensor or electronics technology

- Decreasing Size/Increasing Density
- Constant or Lower Power
- Higher Sensitivity/Response
- Equal or Higher Reliability

- Increasing Complexity
- Increasing Capability
- Increasing Adaptability

- Exploit Nanoscale Phenomenon
- Photon Detection
- Particle/Molecule Detection
- Logic Gate

- First Device Element
  - Single Pixel
  - Memory Bit
  - Logic Operation

- Small Array (Order 100X100)
- Large Array
  - $10^6$ to $10^{12}$

- Laboratory-Scale Fabrication
- Foundry-Scale Manufacturing

- Sensing and Devices
- Intelligent Systems

- Homogeneous Elements
  - (e.g. electrical, molecular, biological or optical)

- Heterogeneous Elements
  - (e.g. electrical, molecular, biological and optical)

- Mission Needs
- Commercial Development
- Broad Community Research
Key Relationships:

- Nanomaterials (16.1):
  Material developments will enable device improvements

- Nano Systems (16.3):
  Sensors/Devices will support development of Systems

- Sensors and Instrumentation (Capability 12):
  - Sensor component developments for In-Situ Sensing (12.6) and Direct Sensing of -- Fields, Waves and Particles (12.5)
  - Improved optical sources/detectors – for Multi-Spectral Imaging / Spectroscopy (12.2) and LASER/LIDAR Remote Sensing (12.4)
  - Principle source of relevant sensor priorities and metrics

- Autonomous Systems & Robotics (Capability 10)
- Human health and Support Systems (Capability 8)
- Robotic Access to Planetary Surfaces (Capability 6)
- Advanced Modeling, Simulation and Analysis (Capability 14)
Capability Breakdown Structure

Science Instruments and Sensors

Chair: Richard Barney NASA/GSFC
Co-Chair: Maria Zuber
Deputy: Juan Rivera NASA/GSFC

Active and Passive Microwave Remote Sensing
12.1
Chair: Soren Madsen JPL
Co-Chair: Chris Ruf/UM

Multi-Spectral Imaging/Spectroscopy (vis-IR-FIR)
12.2
Chair: Craig McCrecht/ARC
Co-Chair: Ron Polidan/NGST

Multi-Spectral Imaging/Spectroscopy (UV-Gamma)
12.3
Chair: Brian Ramsey/MSFC
Co-Chair: David Chenette/LM

Laser/LIDAR Remote Sensing
12.4
Chair: Maria Zuber/MIT
Co-Chair: Richard Barney/GSFC

Direct Sensing of Fields, Waves, and Particles
12.5
Chair: Dick McEntire/APL
Co-Chair: Carl Stahl/GSFC

In Situ
12.6
Chair: Tim Krabach/JPL
Co-Chair: Rich Dissly/BATC

Real Aperture Radar
12.1.1

Synthetic Aperture Radar
12.1.3

Interferometric SAR
12.1.4

Radar Subsurface Sounding
12.1.5

Passive Microwave Real Aperture Imager
12.1.6

Passive Microwave Synthetic Aperture Imagers
12.1.7

Passive Microwave Sounder
12.1.8

GPS – Radio time-of-flight triangulation
12.1.9

Other Technology
12.1.10

Visible Imagery, Photometers, Radiometers, Sounders
12.2.1

Visible Spectrometers / Interferometers
12.2.2

Visible Spectral (hyperspectral) Imagery
12.2.3

IR/FIR Imagery, Photometers, Radiometers, Sounders
12.2.4

IR/FIR Spectrometers / Interferometers
12.2.5

IR/FIR Spectral (hyperspectral) Imagery
12.2.6

UV Imaging and Spectrometry
12.3.1

X-Ray Timing and Polarimetry
12.3.2

X-Ray Interferometry
12.3.3

Gamma Ray Imaging and Spectrometry
12.3.4

Allimeters
12.4.1

Transponders
12.4.2

Atmospheric LIDARS
12.4.3

Spectrometers
12.4.4

Interferometers
12.4.5

Energetic Particle and Plasma Imagers and Spectrometers
12.5.1

High Energy Particle Detector Systems
12.5.2

Magnetometers
12.5.3

Electric Fields and Waves Instruments
12.5.4

Gravitational Waves and Fields Instruments
12.5.5

Imaging/Microscopy
12.6.1

Mineralogical/Elemental Analysis
12.6.2

Chemical Detection & Identification
12.6.3

Isotope Analysis/Age Dating
12.6.4

Biological Detection and Identification
12.6.5

Geophysical Measurements
12.6.6

In Situ Instrument Engineering
12.6.7

Fundamental Technologies and Components
12.6.8

Draft – 02/05
Microwave Instruments and Sensors

- Massively parallel digital correlators - nanoelectronics

Active and Passive Microwave Remote Sensing

- Radiation hardened processors - nanoelectronics

Note: Radiation hardened electronics is a critical cross-cutting technology area for science instruments and sensors

Multi-spectral, VIS-IR-FIR

- Single photon counting sensing in FIR - sensors
- Readout electronics (ex: single electron transistor) - nanoelectronics
- Example: InSb nanowire hyperspectral IR detector, superior to today’s technology in terms of quantum efficiency, higher operating temperature and sensitivity further into the IR.
Multi-spectral, UV-Gamma

- Mega-channel, radiation hard analog electronics - nanoelectronics

Laser/LIDAR

- Higher power lasers which have lifetimes of 5 years - sensors/devices

Direct Sensing of Particles, Fields, and Waves

- Low power, radiation hard, fault tolerant nanoelectronics: emphasis on operation in more radiation harsh, and small satellite constellations
- Miniaturized and sensitive magnetometers - sensors
- High power laser (up to 300 W!) to operate for 5 years - sensors/devices

In-Situ

- Biomarker detection - sensors
- Chemical identification at high spatial resolution - sensors
Electronic Devices

- Micro/Nano Electronics
  CMOS-Based device technologies (TRL 4-8, various ITRS nodes)

- Energy Conversion
  Example: Thermoelectrics (Devices: TRL 1; Materials: TRL 2-3)

- Sources (x-ray, optical)
  Example: Miniaturized X-Ray Source (TRL 5)

- Memory
  Example: CNT based memory (TRL 2-4)
    Nanowire based memory (TRL 2-3)

Representative Examples in Appendix
Nano-electronics: Opportunities and Challenges

Challenges:

• Stay on the ITRS Roadmap
• Assuring space durability
• Develop of reliable designs and fabrication methods for nano-scale devices suitable for heterogeneous integration
• NASA space-qualified electronics ~3 generations behind ITRS roadmap

Opportunities:

• Semiconductor industry is initiating new partnerships with government and academia (including National Research Initiative)
• Partnership with industry can advance technologies for both commercial, NASA needs
• Participation by NASA can ensure that NASA-specific needs are addressed in technology development
Micro-electronics is becoming Nano-electronics

![Graph showing the transition from micro-electronics to nano-electronics over time, with TRL levels indicated for different technology readiness levels (TRL).](www.intel.com/research/silicon/90nm_press_briefing-technical.htm)
Sensing Devices

- Devices for Chem/Bio sensors (TRL 2-3)
  - Example: Conductance-based devices (e.g. nanowires)
- Bioassay/virus/other bioparticles (TRL 1-3)
  - Example: Mass/Resonance based (e.g. cantilever)
- Devices/materials for in-situ, optical-based spectroscopy (TRL 2)
  - Example: Surface Enhanced Raman (SERS) using nanoparticles
- LASERs and Photonic/Optoelectronic devices for remote sensing/imaging (TRL 2-3)
  - Example: Devices employing quantum dots for multi-wavelength detectors, imagers

Representative Examples in Appendix
Challenges:

• Sensor industry not as centralized as microelectronics industry
• Many potential species/quantities to sense
• Many emerging approaches to sensing and electronics: “winners” still TBD

Opportunities:

• Strategic investment will be leveraged with dual-use developments
• Nanosensors will enable miniature instruments for rovers, microcraft, spacecraft
Draft: Roadmaps

- Roadmaps are currently draft only
- Represent first cut at organizing needed technological capability and timelines when it may be available
- Will be modified as more definitive priorities and roadmaps are produced by other capability road mapping teams
There will be a natural progression toward higher density and heterogeneous functionality including to 3-D structures.

### Key Assumptions:
**Scale:** (feature size)
- 2012: 32 nm
- 2015: 22 nm
- 2020: 16 nm

### Capability Roadmap 16:

#### 16.2.1 Sensors
- Advanced environmental sensor suite for life support
- Mars in-situ instruments: organics, mineralogy, biomarker detection
- Analytical sensors for robotic and space missions
- Thermal and energy management
- Single photon detector, single chip optical table

#### 16.2.2 Electronic Devices
- Fault tolerant memory
- Adaptive logic, wireless on-chip
- High ZT thermoelectric devices (cooling and power)

#### 16.2.3 Nanorobotics/Craft
- Fundamental phenomena
- Device models
- Systems modeling including interaction of electronic, mechanical, and fluidic components

#### 16.2.4 Modeling/Simulation
- 2005
- 2010
- 2015
- 2020
Capability 16.2 Sensors and Devices

Key Assumptions:
- Scale: (feature size)

2020
16 nm

Remote Sensing capability for microcraft

2nd Generation analytical sensors and instrumentation

Integrated medical monitoring/therapy

Multifunctional Sensing Systems

Space qualified computing at ITRS roadmap feature size

Lab on a chip

Reconfigurable lab on a chip

Adaptive Nanosystems

Advanced Architectures

Nano-CAD

Nano-CAD + Inverse Problem

There will be a natural progression toward higher density and heterogeneous functionality including to 3-D structures

16.2.1 Sensors

16.2.2 Electronic Devices

16.2.3 Nanorobotics/Craft

16.2.4 Modeling/Simulation

2020
2025
2030
Detailed Roadmaps
## Capability 16.2 Nanotechnology Roadmap

### Key Assumptions:
- ITRS roadmap
- NNI roadmap

### Capability Roadmap 16:
- Advanced environmental sensor suite for Earth science
- Advanced sensor suite for life support
- Sensor Constellations, multipoint environmental
- Sensor Constellations, multipoint environmental
- Advanced sensor suite life detection

### 16.2.1 Sensing

<table>
<thead>
<tr>
<th>Date</th>
<th>Sensing</th>
<th>Sensor on a chip</th>
<th>Instrument on a chip</th>
<th>Lab on a chip</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>Chem Bio:</td>
<td>Multiplex sensing components</td>
<td>Single chip sensing, bioassays</td>
<td>Health monitoring suite</td>
</tr>
<tr>
<td>2010</td>
<td>Photon:</td>
<td>Discrete sources/detectors</td>
<td>Single photon detector, single chip optical table</td>
<td>Network of optical sensor chips</td>
</tr>
<tr>
<td>2015</td>
<td>State Variables/</td>
<td>Imbedded sensors for structural integrity</td>
<td>Imbedded sensors for structural integrity and performance</td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td>Particles: Sensor Systems:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Extreme environment operation:</td>
<td>High Temperature 150-400K</td>
<td>High Radiation, temp and pressure</td>
<td>Venus conditions</td>
</tr>
</tbody>
</table>

There will be a natural progression toward higher density and heterogeneous functionality including to 3-D structures.

**Timeline:**
- 2012: 32 nm
- 2015: 22 nm
- 2020: 16 nm

**Advanced Technologies:**
- Advanced sensor suite life detection
- Sensor Constellations, multipoint environmental
- Vehicle health monitoring
Capability 16.2 Nanotechnology Roadmap

Key Assumptions:
- ITRS roadmap
- NNI roadmap

There will be a natural progression toward higher density and heterogeneous functionality including to 3-D structures.

Capability Roadmap 16:
- Multifunctional Microcraft/Microrovers
- Advanced Life Support System

16.2.1 Sensing
- Lab on a chip
- Reconfigurable lab on a chip

Chem Bio: Health monitoring suite
- Automatic health monitor/response, Integrated Trigger

Photon: Network of optical sensor chips

State Variables/

Particles:
- Sensor Systems:
- Extreme environment operation:
  - Venus conditions
  - Near-Sun conditions

2020 2025 2030
Capability 16.2 Nanotechnology Roadmap

Key Assumptions:
- ITRS roadmap
- NNI roadmap

Capability Roadmap 16:
- 2012: 32 nm
- 2015: 22 nm
- 2020: 16 nm

On-board computing near ITRS performance levels

Fault Tolerant Memory:
- General Computation:
  - Low power, fault tolerant memory architecture; demos of nanoelectronics in extreme environments
- Sense and control:
  - On-chip interfaces and controls
- Special purpose:
  - Ultra-low noise electronics for sensors
  - Integrated sense/computing

Adaptive Logic:
- Low power, adaptive logic;
- NASA electronics near ITRS performance
- Self-adaptive/configurable

Adaptive Nanosystems:
- NASA electronics at ITRS performance levels
- On-board computing near ITRS performance levels

There will be a natural progression toward higher density and heterogeneous functionality including to 3-D structures.

16.2.2 Electronics
- 2005
- 2010
- 2015
- 2020

Ultra-low noise electronics for sensors
On-chip photovoltaics
Flexible electronics
THz Local Oscillator

Draft
Capability 16.2 Nanotechnology Roadmap

Key Assumptions: ITRS roadmap
NNI roadmap

Capability Roadmap 16:
Rad-hard, fault tolerant electronics
Pico probes

16.2.2 Electronics
Adaptive Nanosystems
Advanced Architectures

General Computation:
Self-adaptive/configurable
NASA electronics at ITRS performance

Integrated sense/control:
Integrated sense/electronics

Special purpose:
THz Local Oscillator
Ultra-sensitive atomic interferometric gyroscope

There will be a natural progression toward higher density and heterogeneous functionality including to 3-D structures

2020 2025 2030
Key Assumptions:
ITRS roadmap
NNI roadmap

2012: 32 nm
2015: 22 nm
2020: 16 nm

Capability Roadmap 16:
Thermal and Energy Management

16.2.3 Nanorobotics: TBD
TBD: TBD
TBD: TBD
TBD: TBD

Incomplete

NEMS Devices

Thermal Management:
High ZT
Thermoelectric Devices
(Cooling and Power)

Computing

2005 2010 2015 2025 2030
Capability 16.2 Nanotechnology Roadmap

Key Assumptions:
- ITRS roadmap
- NNI roadmap

Capability Roadmap 16:

16.2.4 Modeling/Simulation

- Fundamental Phenomena
- Device Models
- Systems modeling including interaction of electronic, mechanical and fluidic components

Macro-scale:
- Parametrized circuit models
- Direct coupling of circuit and empirical device models

Meso-scale:
- Empirical device models
- Predictive device models

Nano-scale:
- Fundamental physics/chemistry
- Extreme environment

Software:
- Isolated components
- Integrated frameworks
- Device modeling

2005 2010 2015 2020
Capability 16.2 Nanotechnology Roadmap

Key Assumptions:
- ITRS roadmap
- NNI roadmap

2020
16 nm

Capability Roadmap 16:

Computer and Sensor reliability assurance

16.2.4 Modeling/Simulation

Nano-CAD
Nano-CAD + Inverse Problem

Macro-scale:
- Direct coupling of circuit and predictive device models
- System level simulations directed by specifications

Meso-scale:
- Full many body models
- Full coupling to quantized fields

Nano-scale:
- Integrated frameworks
- Directed system modeling

Software:
- System modeling

2020 2025 2030
Appendix I – Representative Examples of Nano Devices/Sensors

(used in evaluating connectivity to other CRM areas and TRL levels)
• Manufacturable solutions do not exist
  - Oxide thickness scaling, gate capacitance
  - Source-drain resistance
  - Reliable interconnects
• Power delay product is large making chips hot

Downscaling of electronics has major bottlenecks
• SER of a single SRAM decreases with technology generation
• SER of logic increases → Decrease in critical charge involved in latchup

Fabrication and design to avoid latchup become increasingly important
Thermoelectric Energy Conversion

In bulk materials, maximum $ZT \sim 1$
Little progress in 20 years.

Need $ZT \sim 4$ to displace with other technologies

Figure of Merit:

$$ZT = \frac{S^2 \sigma}{\kappa} T$$

Large Seebeck Coefficient ($S$)
Small Thermal Conductivity ($\kappa$)
Large electrical conductivity ($\sigma$)
Nanostructuring materials to improve ZT

Two Dimensional Superlattices

$\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$

Arrays of One-Dimensional Wires

(50 nm Bi$_2$Te$_3$ wires in nanoporous alumina)

Venkatasubramanian, et al. (GTRI), Nature 413 p. 597 (2001)

Source: Tim Sands, Purdue
Carbon-Nanotubes: Sharp local tips provide efficient field emission
Miniature X-Ray tube: slated for 2009 NASA mission

- SWNT - MWNT - nanofibers
- Silicon and metal substrates
- Film, arrays

➢ Optimum type of CNT?
➢ Optimum CNT/substrate attachment?
➢ Optimum site density?
Nanoparticle based structure is produced by self assembly of particles that create a substrate for use in Surface Enhanced Raman Spectroscopy (SERS).

(A) on plasmon resonant substrate with metal nanoparticles (460 nm plasmon maximum), (B) on electrochemically roughened Ag electrode, (C) on laser ablated Ag films (old), and (D) on laser ablated film (new).

Source: Viktor Stolc, NASA Ames Research Center
**Biosensor**

- Optical, Electrical, Mechanical methods for detection

- **Cantilever based sensor**
  - Wu, PNAS (2001)

- **Nanowire**

- **Mass sensing of single virus**
  - Gupta et. al, APL (2004)

- **Detection of mutation causing cystic fibrosis is demonstrated**

- 100 fM DNA solution

- Label free detection of biomolecules in real time
- Cantilever Bending: Probe is attached to top surface. Hybridization causes bending
- Nanowire: Charge of biomolecule affects electrical current in nanowire / nanotube
- Detection of mutation causing cystic fibrosis is demonstrated
- Ultra low detection limits, single particle detection in some cases
Electron-beam fabricated SOI DNA sensor

Chemistry & Mineralogy

- DETECTOR
- SIMULTANEOUS ANALYSES
- NO MOVING PARTS

- Carbon nanotube field emitters
- Low threshold for emission
- Volume < 10 liter (1 liter)
- Mass < 5 kilogram (1 kg)
- Power < 15 Watts (5 W)
Appendix III – Representative Example of potential (and actual) applications in Missions:

In-Situ Science Instruments for Mars
Mars Science in-situ Instruments

Phoenix
Chemical Analysis & Microscopy

Mars Science Laboratory
Organic Detection & Mineralogy

Astrobiology Field Lab
Life Bio-markers Detection and Identification

Time

Draft
Selected In-situ Instruments for Future Mars Missions

Mars 2007 = Phoenix

Chemical analysis & Microscopy
- Thermal and Evolved Gas Analyzer (TEGA)
- Microscopy, Electrochemistry, and Conductivity Analyzer (MECA)

The atomic force microscope will provide morphology images down to 10 nanometers—the smallest scale ever examined on Mars.

Mars 2009 = Mars Science Laboratory

Organic Detection & Mineralogy
Sample Analysis at Mars (SAM)
- Gas Chromatograph
- Mass Spectrometer
- Tunable Laser Spectrometer
  Detection sensitivity of \( \text{ppm-ppb} \)

CheMin
- X-Ray Diffraction/X-Ray Fluorescence Instrument
  (grain size 150 micron)

3D model of the CheMin instrument
Detection and identification of life bio-markers

- Meso-Micro Scale Imaging
- Microscopy
- Mineralogical/Elemental Analysis
- Isotope Analysis/Age Dating
- Bio-Sensors
- Geophysical & Geochemical Measurements
- Compact multi-hyper spectral imagers
  - E-beam fabrication of analog-relief diffractive optics
- Miniaturized Scanning electron microscopy,
  - Sub nm resolution imaging
- Light and tip enhanced AFM,
  - Sub nm resolution imaging
- Fluorescent nano-particulate tagging
- Nano structures based sources (UV, X-Ray, IR)
- Micro-nano electrodes,
- Micro-nano manipulators,
- Array of ion channel sensors
- Array of nano sensors
- Micro-nano fluidics
- Measure pH, temperature, conductivity, and concentrations of major ions and redox sensitive aqueous compounds, including O\textsubscript{2}, H\textsubscript{2}, HCO\textsubscript{3}\textsuperscript{-}, NO\textsubscript{3}\textsuperscript{-}, Fe\textsuperscript{2+}, SO\textsubscript{4}\textsuperscript{2-}, H\textsubscript{2}S, NH\textsubscript{4}\textsuperscript{+} (e.g., microelectrodes, micromanipulators).

- Determine presence (if possible, concentrations) of DOC and aqueous organic monomers, including carboxylic acids, amino acids, sugars, hydrocarbons and/or corresponding functional groups (e.g., liquid and gas chromatography, IR).

- Determine presence (if possible, sequence or composition) of aqueous and particulate organic polymers, including proteins, lipids, nucleic acids, saccharides.

- Attempt to visualize and enumerate variably stained microbial cells in suspension or on particulate matter (e.g., light or scanning electron microscopy, microspectroscopy, fluorescent nanoparticulate tagging).

- Consider culturing on 1-3 samples using ~10-100 pre-designed growth media at several different temperatures (microfluidics, microculturing, “lab-on-a-chip”).
Appendix IV – Excerpts from NNI Grand Challenges Workshop on
Summary Quad Charts for: Nano-Sensor and Instrumentation Nanorobotics
## Nano-sensors and Instrumentation

<table>
<thead>
<tr>
<th>Goals</th>
<th>Hard Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enable missions with nano-sensors:</td>
<td>• Band-gap engineered materials</td>
</tr>
<tr>
<td>• Remote sensing</td>
<td>• Control Atomic layers of substrates</td>
</tr>
<tr>
<td>• Viewing there</td>
<td>• Template pattern controls</td>
</tr>
<tr>
<td>• Vehicle health and performance</td>
<td>• Dark current reductions</td>
</tr>
<tr>
<td>• Getting there</td>
<td>• Readout electronics</td>
</tr>
<tr>
<td>• Geochemical and astrobiological research</td>
<td>• Assembly of large arrays</td>
</tr>
<tr>
<td>• Being there</td>
<td>• Modeling, simulation and testing</td>
</tr>
<tr>
<td>• Manned space flight</td>
<td>• Upward integration into macro-systems</td>
</tr>
<tr>
<td>• Living there</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Value to Space Systems</th>
<th>State of the Art (all ground based)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 10X to 100X smaller, lower power &amp; cost</td>
<td>• Designer bio/chemical sensors</td>
</tr>
<tr>
<td>• Tailorable for very high quantum efficiency</td>
<td>• Characteristic Properties of Molecules</td>
</tr>
<tr>
<td>• Tailorable for space durability in harsh environments</td>
<td>• Functionalized structures (CNTs, etc.)</td>
</tr>
<tr>
<td>• Improved capabilities at comparable or reduced cost</td>
<td>• Assembly of nano-structures</td>
</tr>
<tr>
<td>• Mission enabling technology</td>
<td>• Template development</td>
</tr>
<tr>
<td></td>
<td>• Electro-static control</td>
</tr>
<tr>
<td></td>
<td>• Nano-fluidics/separation tools</td>
</tr>
</tbody>
</table>
# Nanorobotics

## Goals
- Millimeter and sub-millimeter size robots
- 3D nanoassembly and nanomanufacturing
- Self-reconfigurable miniature robots
- Controlling biosystems
- Hybrid (biotic/abiotic) robots
- Cooperative networks of micro-robots
- Atomic and molecular scale manufacturing
- Design and simulation tools for nano-robots

## Hard Problems
- **Mobility**: Surface climbing, walking, hopping, flying, swimming; Smart nanomaterials for adhesion, multi-functionality, …
- **Power**: Harvesting; Novel miniature power systems (e.g. chemical energy); Wireless
- **Actuation**: CNT, polymer, electrostatic, thermal, SMA, and piezo actuators
- **Complexity**: New programming methods for controlling massive numbers of robots

## Value to Space Systems
- In-space (CEV, space station, Hubble telescope, & satellites) and planetary inspection, maintenance, and repair
- Searching for life on planets (retrieving and analyzing samples)
- Astronaut health monitoring
- Assembly and construction
- Manufacturing on-demand
- Microcraft

## State of the Art
- **Miniature Micro/Nano-Robots**: Centimeter scale autonomous robots; Chemically powered bio-motor actuation; Endoscopic micro-capsules; MEMS solar cells powered micro-robots; Reconfigurable mini-robots
- **Micro/Nano-Manipulation**: Scanning Probe Microscope based nanomanipulation; 3D micro-assembly; Optical tweezers and dielectrophoretic bio-manipulation; Virtual Reality human-machine user interfaces
Intelligent / Integrated Systems
Capability 16.3 Intelligent Systems

Presenter/Team Lead:
Chih Ming Ho, UCLA
chihming@ucla.edu

Co-Lead:
Benny Toomarian - JPL

Team Members:
Minoo Dastoor – NASA HQ
Jose Fortes - Univ. of Florida,
Dan Herr - SRC,
Dimitris Lagoudas - Texas A&M Univ.
Stan Williams - HP Labs
• Principles, frameworks, and nano-components for the design, fabrication, integration of mission-appropriate intelligent systems capable of continua of awareness.
Key technical challenges:

- Multiscale hierarchical models for analysis and prediction/design/synthesis of intelligent systems.
- Multiscale manufacturing processes (that can encompass the nano, micro and the macro scales).
- Interconnectivity for signal and material transports.
- Preservation and utilization of nano-properties at the device and system levels.
- Information representation and processing models and architectures from the nano scale to the macro scale that are well suited to emergent
Intelligent systems will benefit:

- Crew health monitoring and drug delivery
  - Cell imaging and penetration
- Crew environment monitoring and control
  - Air and Water purification
- Miniaturized planetary probes, e.g.,
  - Titan probe
  - Mars astrobiology field laboratory
    - Integrated array of nano-sensors with nano fluidics
- Thermal protection system
  - Smart skin
- Large aperture systems
  - Smart skin,
Current State-of-the-Art for Capability 16.3 Intelligent Systems

Multi-scale Hierarchical Modeling. TRL=1-2

- **Robust multi-scale modeling exists from micro to macro for well-understood systems** (excluding, for example, transport-based systems).
- **Quantum-to-Nano-to-Micro modeling is at a primitive state.**
Multi-scale Manufacturing Processes.
TRL = 1-3

• Top-down processes (lithography-based) are highly mature; state of the art at 90 nm half-pitch; limits (ITRS) at 32 nm
• Commercial sensors: biological bio-nano sensors (e.g., dna-based and protein-based) are very mature; limited capability to build integrated sensor systems (exceptional cases exist).
• Design of nanomaterials and upscale to nanocomposites still at infancy (some approaching commercialization).
• Nanoimprinting and related technologies are emerging primarily for research purposes (some commercially available).
• Directed self-assembly still immature.
Interconnectivity. TRL = 2 - 4

- Electronic-based signaling through multi-level metal wires (as in most ICs) is very mature … but reaching limits (ITRS) 90 nm at top level, ~ 8 levels
- Ink-jet printing (as an example of material transport) 3 different fluids and pico-liter drops

Array of ink-jet nozzles for less than pico-liter fluid delivery (Tseng et al, JMEMS 2002)
• Utilization of nano-properties. TRL = 1 to 4
  – Quantum-well structures, giant magneto resistance (GMR) disk reading heads). SOA controlling phenomena in one dimension
  – Commercially available pharmaceuticals exploit designed molecule properties.
  – Quantum-dot based structures for research purposes (for tags)
Information Representation TRL = 1 to 5

- Von-Neumann models/computing is pervasive, dominated by major microprocessor architectures
- Programmable structures (a la FPGA) emerging as alternatives to lithographically-defined designs
- Neural networks/models and genetic algorithmics offer alternatives to programmed von Neumann systems by learning
- Bioinspired/Biomimetic/neuromorphic at research stage
- Emergent untried computing models (QCA, quantum...
• NASA will have a focused effort in nanotechnology
• Substantial progress in nanotechnology will continue based on support from other government and industry participants, which NASA can exploit (e.g. NNI roadmap)
• NASA will actively collaborate with academia and Industry in developments
• Modeling will utilize trend that computing power goes up 100 times every 10 years
• Level of development to TRL 4 in roadmap;
• Other “capabilities” are our principal customers
16.3 Intelligent Systems (capabilities)

16.3.1 Multi-scale Modeling
- Forward Nanoscale Modeling of Nanoscale Component nano-composites
- Integrated regular top-down and undirected bottom-up DNA micro-sensor
- Nanowire Interconnects Crossbar based memory

16.3.2 Multi-scale Manufacturing
- Deep submicron-accurate uniform nanostructures
- Nanostructures based devices

16.3.3 Interconnectivity
- Forward and Inverse Modeling of Nanoscale Component nano-photonics crystals
- Integrated irregular top-down and undirected bottom-up Sub-lithographical irregular arrays
- Material Transport Multiplexing arrayed lab-on-a-chip

16.3.4 Utilization of Nano Properties
- Nanostructures based devices
- Nanometer-accurate uniform nanostructures nano-composites & supramolecules

16.3.5 Information Representation
- Reliable reconfigurable nano-computing
- Nanoscale logic gates

Nanostructures based sources and detectors
Nanomaterial based air & water purification system
Arrayed Lab-on-a-chip

2005 2010 2015
16.3 Intelligent Systems (capabilities)  

**16.3.1 Multi-scale Modeling**  
Nano-micro interface models  
DNA-protein interactions  
supra-molecular structures  
(20 nm3)  

**16.3.2 Multi-scale Manufacturing**  
Directed bottom-up  
Artificial muscle  
Nanowire routing  
(irregular layouts)  
Post-charge signal transfer  

**16.3.3 Interconnectivity**  
Nanoscale module models  
circuits/systems, nano-Spice  
Programmable interconnect for material transport  
3D lab-on-a-chip  

**16.3.4 Utilization of Nano Properties**  
Atomically uniform nanostructures  
Quantum sensors  
Integrated system level reliable nanostructure arrays  
Metrology and structure self aligning to optical tolerances of  
200 picometers  

**16.3.5 Information Representation**  
Distributed reconfigurable systems  
Real Time Diagnosis and Prognosis  

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<tbody>
<tr>
<td>Scientific Instruments and Sensors</td>
<td>Reliable nanoscale module</td>
<td>Large array systems (artificial skin)</td>
<td>Biotic – abiotic interconnection (artificial retina)</td>
<td>Integrated system level reliable nano-structure arrays</td>
<td>Biologically inspired high-distributed intelligent systems</td>
</tr>
<tr>
<td>Human Health and Support Systems</td>
<td>Reliable nano-micro interface models (DNA-Protein)</td>
<td>Fully integrated general bottom up (self-healing materials)</td>
<td>Bio-electronic signaling for integrated non-invasive monitoring tools</td>
<td>Diagnosis and utilization of appropriate devices</td>
<td>Real Time Diagnosis and Prognosis</td>
</tr>
</tbody>
</table>
Summary and Next Steps
Mission Needs/Opportunity Timeline for Nanotechnology

1st Generation:
- Power Generation/Storage, Life Support, Astronaut Health Mgt, Thermal Mgt.
- High Strength, Lt. Wt./Multifunctional Structures

Radiation Protection, Advanced TPS

Humans to the Moon

Crew Exploration Vehicle

Mars Transfer Vehicle

Humans to Mars

Lunar and Mars Robotics Precursor

Mars robotic missions (every 2 years)

Robotic Missions to Extreme Environments After Mars (Outer Solar System, Venus …)

Deep Space Constellations (X-Ray Telescope, Earth’s Magnetosphere, …)

Large Scale Interferometry (Planetary Finding)

Very Long Baseline Interferometry (Planetary Imaging)

Greatly miniaturized robotic systems: 1 kg-sats/robots with the capability of today’s 100 kg systems (Mars and other planetary bodies: in orbit, atmospheres, surfaces, sub-surfaces)

Large, lightweight highly stable optical and RF apertures and metering structures (~10m)

High Altitude Long Endurance Aircraft

“Planetary Aircraft” (e.g. Mars)

Lt. Weight High Strength Structures
Low Power Avionics
Lightweight, High Efficiency Electrical Power Systems (Solar Arrays, Regenerative Fuel Cells)

1st Generation Zero Emissions Aircraft

2nd Generation
- Power Generation/Storage, Life Support, Astronaut Health Mgt, Thermal Mgt.
- High Strength/Multifunctional Structures

Humans to the Moon

Crew Exploration Vehicle

Mars Transfer Vehicle

Humans to Mars

Lunar and Mars Robotics Precursor

Mars robotic missions (every 2 years)

Robotic Missions to Extreme Environments After Mars (Outer Solar System, Venus …)

Deep Space Constellations (X-Ray Telescope, Earth’s Magnetosphere, …)

Large Scale Interferometry (Planetary Finding)

Very Long Baseline Interferometry (Planetary Imaging)

Extremely large, lightweight, highly stable optical and RF apertures and metering structures (~10-100 m)

(Continued on the next page)
## Nanotechnology Top Level Capability Roadmap (Exploration)

### 1st Generation:
- Power Generation/Storage,
- Life Support,
- Astronaut Health Mgt,
- Thermal Mgt.

### 2nd Generation:
- Power Generation/Storage,
- Life Support,
- Astronaut Health Mgt,
- Thermal Mgt.

### Humans to the Moon
- Crew Exploration Vehicle
  - High Strength, Lt. Wt./Multifunctional Structures

### Mars Transfer Vehicle
- Lightweight Fuel Tanks, Radiators (Nuclear Prop.)
- High Strength/Multifunctional Structures

### Humans to Mars
- Lunar and Mars Robotics Precursor
  - High Strength, Lt. Wt./Multifunctional Structures

### Roadmap 16: Nanotechnology

#### 16.1 Nanometrically Structured Materials
- Nanocomposite with 5000X lower permeability
- High Temp Nanomaterial TPS w/50% lower mass
- Flexible, ultralow density insulation
- High Specific Power Storage
- Nanomaterial fuel cell MEA with 50% higher power density
- Multifunctionality, Radiation Shielding

#### 16.2 Sensing and Devices
- Sensor on a chip
- High Temp. Components
- Rad-hard fault tolerant electronics
- Ultra-low power adaptable logic
- Ultra-low noise electronics for sensors
- On-chip photovoltaics
- Ultra-sensitive atomic interferometric gyroscope
- Adaptive nano electronics

#### 16.3 Intelligent Integrated Systems
- Nanostructures based sources and detectors
- Arrayed Lab-on-a-chip
- Lab in a Tea Cup
- Self-Healing Materials
- “Artificial skin”

### Timeline
- 2005
- 2010
- 2015
- 2020
- 2025
- 2030

---

*Draft*
**Nanotechnology Top Level Capability Roadmap (Aeronautics)**

**Capability Roadmap 16: Nanotechnology**

### 16.1 Nano-Structured Materials
- Nanocomposite with 5000X lower permeability
- Low Density, High Stiffness
- Nanomaterial fuel cell MEA with 50% higher power density
- High strength, lightweight composites & cables

### 16.2 Sensing and Devices
- Rad-hard fault tolerant electronics
- Ultra-low power adaptable logic
- Single chip, durable
- Temp., Pressure and Strain sensing
- Distributed reconfigurable systems

### 16.3 Intelligent Integrated Systems
- Artificial Muscle
- Self-Healing Materials

**High Altitude Long Endurance Aircraft**
- Lt. Weight High Strength Structures
- Low Power Avionics

**“Planetary Aircraft” (e.g. Mars)**
- Nanotube wires with 10X higher conductivity than Copper
- High strength, lightweight composites & cables

**1st Generation Zero Emissions Aircraft**
- Low Power Avionics
- Nanotube wires with 10X higher conductivity than Copper
- High strength, lightweight composites & cables

**2005** | **2010** | **2015** | **2020** | **2025** | **2030**
---|---|---|---|---|---

--- Draft ---
Next Steps

- Make changes to roadmaps based on verbal feedback from NRC review
- Receive the draft Strategic Roadmaps
- Review and Assess all applicable Strategic Roadmaps and their requirements for Nanotechnology capability
- Make changes to Nanotechnology roadmaps to ensure consistency with Strategic Roadmaps requirements and other Capability Roadmaps
- Develop rough order of magnitude cost estimates for the Nanotechnology Capability Roadmap
- Prepare for 2nd NRC Review which will address 4 additional questions:
  - Are there any important gaps in the capability roadmaps as related to the strategic roadmap set?
  - Do the capability roadmaps articulate a clear sense of priorities among various elements?
  - Are the capability roadmaps clearly linked to the strategic roadmaps, and do the capability roadmaps reflect the priorities set out in the strategic roadmaps?
  - Is the timing for the availability of a capability synchronized with the scheduled need in the associated strategic roadmap?
Closure and Crosswalk
(with other Roadmaps)
“Closure”

**Co-Chairs:**
- M. Dastoor (NASA HQ)
- M. Hirschbein (NASA HQ)
- D. Lagoudas (Texas A&M)
Nanotechnology Closure

- Challenges
- Crosswalk
- Status
- Forward Work
Challenges

Technical
- Production of nanomaterials
- Characterization at both atomic and bulk scale
- Modeling & Simulation
- Applications Development
- System Integration

Managing Expectations (Most Difficult)
- Strongly advocate potential benefit
- Be responsive to needs of future technology users
- Avoid hype at all cost

Institutional
- Coordination/Cooperation among NASA/Industry/Academia/OGA
- Long-term Stability

“Roadmapping”
- Organization
- Condensation
- Connection
Technical Challenges

• Production of nanomaterials
  - Quantity, quality, control of properties & production in specified forms

• Characterization at both atomic and bulk scale
  - Fundamental mechanical, electrical and optical properties

• Modeling & Simulation
  - Prediction of physical/chemical properties and behavior from nanoscale to macroscale as well as models for material production

• Applications Development
  - Tools and techniques for applications of nanotechnology
  - Verification of predicted behavior/performance in actual environments
  - Systems Analysis to guide technology development

• System Integration
  - Macro-scale assembly and fabrication
  - Validation testing
Major “Roadmapping” Challenge

- **Organization, Condensation and Connection**
  - Nanotechnology is extremely broad and deep
  - Multiple ways to present scope and content of nanotechnology
  - Being concise without loosing content -- nanotechnology affects many aspects of all other capability areas
  - Clearly show projection in to other capability areas

Major Institutional Challenges

- **Coordination/Cooperation among NASA/industry/academia/OGA**
  - Many common interests but different missions and priorities
  - All too often the attitude is, ‘why do we need to invest in nanotechnology too?’
  - Need to incentivize major industry: partnerships, long-range planning, investment, ….

- **Long-term stability**
  - Budget, education
  - Infusion of nanotechnology products into plans and missions ("crossing the valley of death between proof-of-concept and prototype")
<table>
<thead>
<tr>
<th>Impact:</th>
<th>Highest</th>
<th>Next Highest</th>
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<tbody>
<tr>
<td><strong>Nanotechnology Crosswalk (Space)</strong></td>
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<tr>
<td><strong>High Energy Power and Propulsion</strong></td>
<td>Very high efficiency PV, electrodes for advanced batteries, materials for high power fly wheels, supercapacitors, advanced thermoelectric materials, fuel cell membranes, light weight radiators and H2 tanks…</td>
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<td><strong>In-Space Transportation</strong></td>
<td>Advanced high strength, lightweight structural materials</td>
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<td><strong>Advanced Telescopes and Observatories</strong></td>
<td>Lightweight, high stiffness, low CTE materials for optics and large structures, thermal coatings…</td>
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<td><strong>Robotic Access to Planetary Surfaces</strong></td>
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<td>Lightweight thermal protection</td>
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<td><strong>Human Planetary Landing Systems</strong></td>
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<td><strong>Human Health and Support Systems</strong></td>
<td>Health monitoring, diagnosis; membranes for life support processes (e.g. air purification, catalysis), radiation protection…</td>
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<tr>
<td><strong>Human Exploration Systems and Mobility</strong></td>
<td>Sensors, electronics, materials (light weight, high strength; high thermal conductivity; radiation protection; self-healing,….)</td>
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<tr>
<td><strong>Autonomous Systems &amp; Robotics</strong></td>
<td>Low power computing and electronics; systems for sub-kg rovers</td>
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<td><strong>Scientific Instruments and Sensors</strong></td>
<td>Ultra-sensitive, environmentally robust detectors; compact active sources (laser, X-ray, sub-mm); high temperature IR detectors…</td>
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<td><strong>In-Situ Resource Utilization</strong></td>
<td>Process monitoring sensing, catalysis and filtration</td>
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<td><strong>Communications and Navigation</strong></td>
<td>Advanced low power electronic and photonic devices and systems</td>
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<td><strong>Transformational Spaceport/Range</strong></td>
<td>Sensing for environmental monitoring</td>
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<td><strong>Advanced Modeling Simulation &amp; Analysis</strong></td>
<td>Multi-scale modeling for materials, devices and systems</td>
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<td><strong>Systems Engineering Cost/Risk Analysis</strong></td>
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<td>Nanotechnology Crosswalk (Aero)</td>
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<td>Advanced high strength/stiffness, lightweight structural materials</td>
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A high degree of commonality between aeronautics and space applications
Status

• Current roadmapping waypoint, about mid-way to two-thirds
  - Work-in-progress
  - Significant work left to do

• In a “forward-looking” mode
  - Strategic roadmaps under development
  - Other capability roadmaps under parallel development with nanotechnology
  - Current nanotechnology roadmap based on “experience and knowledge”

• After NRC reviews (end of March) other 14 capability roadmaps will be available
  - Hold 3rd team workshop
  - Review and revise nanotechnology
  - Address institutional issues

• Further convergence after strategic roadmaps developed
Forward Work

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Mature, Proven but Bounded Technology

New, Unproven but "Unbounded" Technology

"Old-Guard" Technology

Technology Limits

"New Era" Technology

Mission Needs

Oops! Maybe We Should Work Together.