Nanotechnology Presentation Agenda
<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>7:30</td>
<td>Continental Breakfast</td>
</tr>
<tr>
<td>8:00</td>
<td>Welcome and Review Process, Panel Chair &amp; NRC Staff</td>
</tr>
<tr>
<td>8:15</td>
<td>Introduction by APIO to NASA Capability Roadmapping</td>
</tr>
<tr>
<td>8:50</td>
<td>Nanotechnology Presentation Agenda</td>
</tr>
<tr>
<td>9:00</td>
<td>Background: Nanotechnology at NASA</td>
</tr>
<tr>
<td>9:45 - 10:15</td>
<td>Break</td>
</tr>
<tr>
<td>10:15</td>
<td>Overview and Summaries of Roadmapping Activity</td>
</tr>
<tr>
<td>10:45</td>
<td>Nano-Structured Materials</td>
</tr>
<tr>
<td>11:15</td>
<td>Sensors and Devices</td>
</tr>
<tr>
<td>11:45 - 12:45</td>
<td>Lunch</td>
</tr>
<tr>
<td>12:45</td>
<td>Intelligent/Integrated Systems</td>
</tr>
<tr>
<td>1:15</td>
<td>Summary and Next Steps</td>
</tr>
<tr>
<td>1:30</td>
<td>Closure and Crosswalk (with other Roadmaps)</td>
</tr>
<tr>
<td>2:00</td>
<td>Open Discussion</td>
</tr>
<tr>
<td>3:30</td>
<td>Break/NRC Panel Closed Session</td>
</tr>
<tr>
<td>4:15</td>
<td>NRC Panel Discussion with NASA</td>
</tr>
<tr>
<td>5:00</td>
<td>Adjourn</td>
</tr>
</tbody>
</table>
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

Converging Technologies

Grand Challenges

Capability Roadmap: Nanotechnology
Interdisciplinary “horizontal” Knowledge Creation

with “vertical” transition from basic concepts to Grand Challenges and technology integration - Converging Technologies

Fundamental research at the nanoscale

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

NASA’s Strategic Enterprises

- Exploration Systems
- Aeronautics Research
- Space Operations
- Science
• Enable human and robotic exploration

- **Lunar Robotic**
  - ISS Complete
  - Crew Exploration Vehicle
  - Lunar Robotic

- **Mars Robotic**
  - Mars Manned

- **Deep Space Exploration**
  - Lunar Manned

- **Timeline**
  - 2005
  - 2010
  - 2015
  - 2020
  - 2035

---

- Draft —
Capability Roadmap: Nanotechnology

Astronaut Health Management

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

Draft
Exploring Mars

Capability Roadmap: Nanotechnology
Towards Convergence

Climate History
Sample Selection
Ancient Water
Validate Paleo-Life
Resources
Extant Life?

DISCOVERY
EXPLORATION

ROBOTICS
ROBOTICS
ROBOTICS
HUMANS
ROBOTICS & HUMANS

Reconnaissance
Site Selection
Sample Selection
Return Sample
Field Studies
Deep Drilling
The Bigger Picture…

Dynamic Space and Earth Science Events

- CME
- Gamma Ray Burst
- Mars Dust Devils
- Surface Flow
- In Lava Flow
- Hurricane
- Volcanic Ash Plume

Observing Sensor Webs: A System of Systems

Capability Roadmap: Nanotechnology
Hydrogen fuel, electric propulsion – zero environmental impact

Clean and Quiet Aircraft

- Light Weight
- High Strength
- High Reliability
- High Efficiency

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

Science and....

“Perpetual Flight”

Exploration ....

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

- Power Generation & Energy Storage
- Propulsion & Hydrogen Storage
- Low Areal Density Structures
- 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

- **Princeton**
- **UCSB**
- **Northwestern**
- **U of NC**
- **Nat’l Inst. Aerospace**

Institute for Nanoelectronics and Computing (INAC)

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

- **Purdue**
- **Yale**
- **Northwestern**
- **U of Fl**
- **Cornell**
- **Texas A&M**
- **UCSD**

Center for Cell Mimetic Space Exploration (CMISE)

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

- **UCLA**
- **CIT**
- **Ariz. St**
- **UCI**

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

- **Texas A&M**
- **Rice**
- **Texas Southern**
- **Prairie View A&M**
- **U of T-A**
- **U of Houston**
Capability Roadmap: Nanotechnology

Electron Sources - Application Regimes
Capability Roadmap: Nanotechnology
Future Research Directions

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)

- **SRO: Science Relay Orbiter**
  - 3.3 Mrad
    - During a 30-day Period In Europa orbit
  - 3.2 Mrad
    - Over 1-2 years in Jupiter orbit before Europa Landing

Current Missions
- Iridium
- Intelsat
- Galileo

Planned Missions
- MEO Telecom Sats
- 10-12 year duration
- 10 year duration
- 7 year duration

- Europa Orbiter (X2000)
- Galileo
- Intelsat
- MEO
- Telecom Sats
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

a) 60 nm half-pitch crossbar array

b) 100 μm scale view

c) 10 μm scale view

d) 1 μm scale view

e) 100 nm scale view

60 nm half-pitch
ef) 2D and 3D representation

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

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

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

Nanorobotics
Actuation and Control
Molecular Actuation
Micromachines

Nanotechnology Main Themes
- Actuation and Control
- Sensors / Instrumentation
- Electronics
- New algorithms
- Communications

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

Nanomaterials
Structural
Power / Energy Storage
Thermal Management
Shielding
Multifunctionality

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 -
Goals
- 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

Value to Space Systems
- 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

Hard Problems
- 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

State of the Art
- 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
### 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

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)
Content

• 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)

### Industry

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

### 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)

### Coordinators

- **Directorate:** Harley Thronson (Science)  
- **APIO:** Julie Crooke (GSFC)

---

* University Research Engineering and Technology Institute
NASA Co-Chair: Minoo Dastoor

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

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)
- 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)

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)

High Altitude Long Endurance Aircraft

“Planetary Aircraft” (e.g. Mars)

1st Generation Zero Emissions Aircraft

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

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


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

Humans to Mars
- Mars Transfer Vehicle
- Humans to Mars

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

 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

2005 2015 2025 2035
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
• 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
### Why Nanotechnology

#### Mechanical

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strength</strong></td>
<td>nano length scales below Griffith criteria</td>
</tr>
<tr>
<td><strong>Toughness</strong></td>
<td>distributed deformation at nanolength scales</td>
</tr>
<tr>
<td><strong>Damping</strong></td>
<td>efficient energy dissipation at nano-interfaces, nanomorphology, increased</td>
</tr>
<tr>
<td></td>
<td>viscoelasticity with nanoparticle addition</td>
</tr>
<tr>
<td><strong>Hardness</strong></td>
<td>supermodulus effect - nanoscale inclusions</td>
</tr>
<tr>
<td><strong>Modulus/Stiffness</strong></td>
<td>enhanced molecular alignment- more perfect structures - achieve theoretical</td>
</tr>
<tr>
<td><strong>Recoverable strain</strong></td>
<td>quantum level nanoeffects,</td>
</tr>
<tr>
<td><strong>Compressive</strong></td>
<td>toughened interfaces through nanoscale particles, nanovoids</td>
</tr>
<tr>
<td><strong>Impact/Dynamic Loading</strong></td>
<td>nanomorphology effects on energy dissipation</td>
</tr>
<tr>
<td><strong>Friction and Wear</strong></td>
<td>tailored nanostructures to fit asperities</td>
</tr>
</tbody>
</table>

#### Thermal

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conductivity/Insulation</strong></td>
<td>geometry and size effects at a wide range of temperatures (cryo to reentry)</td>
</tr>
<tr>
<td><strong>CTE</strong></td>
<td>nanoscale morphology (voids) effects, phonon coupling, enables</td>
</tr>
<tr>
<td></td>
<td>tailorable CTE</td>
</tr>
<tr>
<td><strong>Emissivity</strong></td>
<td>enhanced surface area/roughness, possible quantum effect</td>
</tr>
</tbody>
</table>
## Benefits of 16.1 Nanostructured Materials

### Why Nanotechnology

#### Electrical

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<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>
</tbody>
</table>

#### Optical

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<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, tailorbility</td>
</tr>
<tr>
<td>Porosity</td>
<td>hierarchical distribution, functionalization</td>
</tr>
</tbody>
</table>
### Why Nanotechnology

<table>
<thead>
<tr>
<th>Why Nanotechnology</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mass Transport/Permeability</strong></td>
</tr>
<tr>
<td>nanoscale morphology (voids) effects, length scale effects on diffusion mechanisms</td>
</tr>
<tr>
<td><strong>Density</strong></td>
</tr>
<tr>
<td>nanomorphology (inclusion of nanopores)</td>
</tr>
<tr>
<td><strong>Environmental</strong></td>
</tr>
<tr>
<td><strong>Radiation</strong></td>
</tr>
<tr>
<td>electronics (smaller cross-section, redundancy, spintronics), human (size effects on energy dissipation??, design flexibility)</td>
</tr>
<tr>
<td><strong>Temperature Stability/Performance</strong></td>
</tr>
<tr>
<td>nanoscale morphology (new interfaces), inhibits degradation (diffusion)</td>
</tr>
<tr>
<td><strong>Corrosion</strong></td>
</tr>
<tr>
<td>surface area, interface tailoring</td>
</tr>
<tr>
<td><strong>Magnetic</strong></td>
</tr>
<tr>
<td>size effect</td>
</tr>
<tr>
<td><strong>Piezoelectric</strong></td>
</tr>
<tr>
<td>size effect</td>
</tr>
<tr>
<td><strong>Chemical Reactivity</strong></td>
</tr>
<tr>
<td>surface area, interface tailoring</td>
</tr>
<tr>
<td><strong>Materials Interactions</strong></td>
</tr>
<tr>
<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.

![Diagram of various spacecraft and applications](image)
Nanostructured Materials are Critical for Future Aeronautics Demonstrators

- **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

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
<table>
<thead>
<tr>
<th>Capability</th>
<th>Year</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.1: Nanostructured Materials</td>
<td>2020</td>
<td>40-60GPa Tensile Strength Nanotube Fiber</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High Temp Nanomaterial TPS with 50% lower mass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nanocomposite with 5X Strength</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ceramic nanomaterial with 1000X toughness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flexible, Rad Hard Quantum Dot PV materials with 50% efficiency</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bulk nanocomposite with thermal conductivities 2X that of diamond</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nanocomposite with thermal conductivities 2X that of diamond</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nanomaterial based active radiation protection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Functionalized Nanomaterials for Cell Repair</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nanoshells for Diagnostics and Photodynamic Therapy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nanocrystalline Materials for Rad Hard Electronics</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nanotube Ribbons with Diamond-like Thermal Conductivity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solid Polymer Electrolyte for -70°C Li-polymer Battery</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High Temp Nanomaterial TPS with 50% lower mass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High strength, low density polymer composite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Improved durability, high strength ceramics</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High strength, lightweight fibers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High Spectral Absorption, Efficient Electron Transfer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low Mass, High Thermal Conductivity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low Mass, Low Thermal Conductivity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low Mass, Highly Efficient Thermal Conductivity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Efficient, Tailorable Radiation Protection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Radiation Protection/Resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Biocompatibility, Biostealactivity, Optical Absortion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Biocompatibility, Optical Properties, Biocompatibility</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Biocompatibility, Biospecificity</td>
</tr>
</tbody>
</table>

- Draft -
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 bumpers 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
- 20% Lighter Airframe and Propulsion Structures

**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

**Timeline:**
- 2005
- 2010
- 2015
Capability 16.1 Nanostructured Materials Roadmap

Key Assumptions:
Potential NASA Applications

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

Enables ultralightweight tethers

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

Capability Roadmap 16.1: Nanostructured Materials

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

- Functionalization for improved interface
- Controlled nanotube synthesis and purification
- Nanostructured membrane development
- Nanostructured catalyst development
- High surface area nanoparticle support
  - 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 $10^{-4}$ Scm$^{-1}$ conductivity at RT
- Nanomaterial fuel cell MEA with 50% higher power density
- Nanotube wires with 10X higher conductivity than Copper

2005  2010  2015
Capability Roadmap 16.1: Nanostructured Materials

Key Assumptions: Potential NASA Applications

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

Capability Roadmap 16.1: Nanostructured Materials

16.1.2 Efficient Power and Energy

- Solid Polymer Electrolyte for -70°C Li-polymer Battery
- Flexible, Rad Hard Quantum Dot PV materials with 50% efficiency
- High ionic conductivity at -70°C
- High Spectral Absorption, Efficient Electron Transfer

Polymer nanocomposites for enhanced ion mobility
Processing, structure for optimum phase separation
Controlled (size, chirality) nanoparticle synthesis
Functionalization/Interface control

- 2020
- 2025
- 2030

Ready to Use
Major Decision
Major Event / Accomplishment / Milestone

Draft
• 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

2005  2010  2015
Capability 16.1 Nanostructured Materials Roadmap

Key Assumptions:
- Potential NASA Applications
- Reduced Vehicle Mass
- Reduced Mass, Efficient, Passive Thermal Control

Capability Roadmap 16.1: Nanostructured Materials
- High Temp Nanomaterial TPS with 50% lower mass
- Nanotube Ribbons with Diamond-like Thermal Conductivity
- Bulk nanocomposite with thermal conductivities 2X that of diamond

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

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

2020 2025 2030
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
Functionality for enhanced dispersion
Processing and in situ process monitoring
Functionality for enhanced interface
Enhanced alignment during processing

Nanoparticle design for enhanced radiation protection
Functionality for optimum interface and dispersion
Understanding effects of structure on radiation protection capability

2005 2010 2015

– Draft –
Key Assumptions:
Potential NASA Applications

Capability Roadmap 16.1: Nanostructured Materials

16.1.4 Radiation and E&M 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

Radiation Hard Electronics, Sensors
Nanocrystalline Materials for Rad Hard Electronics
Nanomaterial based active radiation protection

Advanced Radiation Shielding for Vehicles, Rovers, Habitats
Efficient, Tailorable Radiation Protection

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

Capability Roadmap 16.1: Nanostructured Materials

Water Purification for Vehicles and Habitats
Nanomaterial Water Filtration
Quantum Dot Flow Cytometer for Astronaut Health Management
Nanomaterial Based Air Revitalization

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

Nanoparticle synthesis and purification
Functionalization for chemical/biochemical species removal
Processing for controlled nanoporosity

Quantum dot design, synthesis and purification
Biocompatibility studies
Functionalization for compatibility and detection

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 Absorption
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 Arrays for Multicomponent Bioassays for Astronaut Health

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

2020 2025 2030

-- Draft --
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).

Technology Roadmap Diagram

- Technology Options at Technology Nodes
  - 45 nm: EUV, EPL, ML2, Reticle lithography
  - 32 nm: EUV, EPL, ML2, Reticle lithography
  - 22 nm: Innovative technology
  - 16 nm: Innovative technology

- DRAM Half-pitch (Dense lines)
- Retention enhancement technology (RET)
- Extreme ultraviolet (EUV)
- Maskless lithography (ML2)
- Proximity electron lithography (PEL)

Legend:
- Research Required
- Development Underway
- Qualification/Pre-Production
- Continuous Improvement

Notes:
- Technologies shown in italics have only single region support.
- RET — Retention enhancement technology
- EUV — Extreme ultraviolet
- ML2 — Maskless lithography
- PEL — Proximity electron lithography
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

- 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

- Single Point Sensing
- Multi-point Sensing & Correlation

- Increasing Complexity
- Increasing Capability
- Increasing Adaptability

- 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

- 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

- Single Point Sensing
- Multi-point Sensing & Correlation

- Increasing Complexity
- Increasing Capability
- Increasing Adaptability

- Sensing and Devices
- Intelligent Systems

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

- Heterogeneous Elements
  (e.g. electrical, molecular, biological and optical)
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)**
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. The graph plots feature size and gate length against TRL levels from 1970 to 2020. The TRL levels are marked as TRL 1-2, TRL 4-5, TRL 8-9.](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
Nano-sensors: Opportunities and Challenges

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
• 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
Capability 16.2 Sensors and Devices

Key Assumptions:
Scale: (feature size)

Capability Roadmap 16:

16.2.1 Sensors
Advanced environmental sensor suite for life support

16.2.2 Electronic Devices
Fault Tolerant Memory

16.2.3 Nanorobotics/Craft
Mars in-situ instruments: organics, mineralogy, bio marker detection

16.2.4 Modeling/Simulation
Fundamental Phenomena

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

2005 2010 2015 2020

Sensor on a Chip
Instrument on a Chip
Fault tolerant nanoelectronic devices for microcraft

Fault tolerant memory
Adaptive Logic, Wireless on-chip

Analytical sensors for robotic and space missions
Thermal and energy management

High ZT Thermoelectric Devices (Cooling and Power)
Device Models

Single photon detector, single chip optical table

Systems modeling including interaction of electronic, mechanical and fluidic components

NASA

Advanced Planning & Integration Office
There will be a natural progression toward higher density and heterogeneous functionality including to 3-D structures.
Detailed Roadmaps
Key Assumptions:
ITRS roadmap
NNI roadmap

Capability Roadmap 16:

16.2.1 Sensing

<table>
<thead>
<tr>
<th>2005</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>2015</td>
<td>2020</td>
<td></td>
</tr>
<tr>
<td>32 nm</td>
<td>22 nm</td>
<td>16 nm</td>
<td></td>
</tr>
</tbody>
</table>

- Advanced environmental sensor suite for Earth science
- Vehicle health monitoring
- Sensor Constellations, multipoint environmental
- Advanced sensor suite for life support
- Advanced sensor suite life detection

Chem Bio:

- Multiplex sensing components
- Single chip sensing, bioassays
- Health monitoring suite

Photon:

- Discrete sources/detectors
- Single photon detector, single chip optical table
- Network of optical sensor chips

State Variables:

- Imbedded sensors for structural integrity
- Imbedded sensors for structural integrity and performance

Particles:

- Wireless comm for distributed sensors
- Distributed sensors with Integrated communication

Extreme environment operation:

- High Temperature 150-400K
- High Radiation, temp and pressure
- Venus conditions
Capability 16.2 Nanotechnology Roadmap

Key Assumptions:
- ITRS roadmap
- NNI roadmap

In-situ Human Health Monitoring

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/
- Distributed sensors
- Integrated communication

Particles:
- Venus conditions

Sensor Systems:
- Large-scale wireless sensor systems

Extreme environment operation:
- Near-Sun conditions

2020
2025
2030
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.

<table>
<thead>
<tr>
<th>Year</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>32 nm</td>
</tr>
<tr>
<td>2015</td>
<td>22 nm</td>
</tr>
<tr>
<td>2020</td>
<td>16 nm</td>
</tr>
</tbody>
</table>

16.2.2 Electronics
- Fault Tolerant Memory
  - Low power, fault tolerant memory architecture; demos of nanoelectronics in extreme environments
  - Highly reliable non-volatile on-board memory

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

- Adaptive Nanosystems
  - NASA electronics at ITRS performance
  - Integrated sense/computing

General Computation:
- Sense and control: On-chip interfaces and controls
- Special purpose: Ultra-low noise electronics for sensors

Other Technologies:
- On-chip photovoltaics
- Flexible electronics
- THz Local Oscillator

2005 2010 2015 2020
Capability 16.2 Nanotechnology Roadmap

Key Assumptions:
ITRS roadmap
NNI roadmap

2020
16 nm

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

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

Spintronics
Quantum computing

Integrated sense/control:
Integrated sense/electronics

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

2020 2025 2030
Capability 16.2 Nanotechnology Roadmap

Key Assumptions:
- ITRS roadmap
- NNI roadmap

<table>
<thead>
<tr>
<th></th>
<th>2012</th>
<th>2015</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>32 nm</td>
<td>22 nm</td>
<td>16 nm</td>
</tr>
</tbody>
</table>

Capability Roadmap 16:
Thermal and Energy Management

16.2.3 Nanorobotics
- TBD
- TBD
- TBD
- TBD

Incomplete

NEMS Devices

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

2005 2010 2015 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

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

Years:
- 2005
- 2010
- 2015
- 2020
Capability 16.2 Nanotechnology Roadmap

Key Assumptions:
- ITRS roadmap: 2020
- NNI roadmap: 16 nm

Capability Roadmap 16:

16.2.4 Modeling/Simulation

Nano-CAD

Nano-CAD + Inverse Problem

Computer and Sensor
reliability assurance

Macro-scale:
- Direct coupling of
circuit and predictive
device models

Meso-scale:
- System level
simulations directed
by specifications

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

Software:
- Integrated
frameworks
- System modeling
- Integrated frameworks
directed 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
Soft Error Rate (SER)

- 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

P. Shivakumar et. al,
2002 IEEE Dependable Systems and Networks
Thermoelectric Energy Conversion

Figure of Merit:

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

In bulk materials, maximum $ZT \sim 1$

Little progress in 20 years.

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

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

Two Dimensional Superlattices

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

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

Silicon Nanowire (20 nm) based

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
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
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 ppm-ppb

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

3D model of the CheMin instrument

3D model of SAM 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

Astrobiology Field Lab

Deep Drill Lander
Example of Capabilities Enabled or Enhanced by Nano Technologies

- 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$_2$, H$_2$, HCO$_3^-$, NO$_3^-$, Fe$^{2+}$, SO$_4^{2-}$, H$_2$S, NH$_4^+$ (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

### Goals
Enable missions with nano-sensors:
- Remote sensing
  - Viewing there
- Vehicle health and performance
  - Getting there
- Geochemical and astrobiological research
  - Being there
- Manned space flight
  - Living there

### Value to Space Systems
- 10X to 100X smaller, lower power & cost
- Tailorable for very high quantum efficiency
- Tailorable for space durability in harsh environments
- Improved capabilities at comparable or reduced cost
- Mission enabling technology

### Hard Problems
- Band-gap engineered materials
- Control Atomic layers of substrates
- Template pattern controls
- Dark current reductions
- Readout electronics
- Assembly of large arrays
- Modeling, simulation and testing
- Upward integration into macro-systems

### State of the Art (all ground based)
- Designer bio/chemical sensors
  - Characteristic Properties of Molecules
  - Functionalized structures (CNTs, etc.)
- Assembly of nano-structures
  - Template development
  - Electro-static control
  - Nano-fluidics/separation tools
## 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.

Guided entry for energy dissipation or precision / pinpoint landing

Monitoring & Controlling the environment
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,
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.
Current State-of-the-Art for Capability 16.3 Intelligent Systems

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) 8 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, spintronics, ...)

Diagram:
- Extend CMOS
- QCA
- Spintronics
- NEW SWITCH
- Molecular Electronics
- RTD
- Single Electronics
- 1D-devices
- 1D-devices
- 1D-devices
- 1D-devices
• 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
- Nanoscale logic gates

**16.3.3 Interconnectivity**
- 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**
- Forward and Inverse Modeling of Nanoscale Component nano-photonics
- Sub-lithographical irregular arrays
- Nanometer-accurate uniform nanostructures
- Nano-composites & supramolecules

**16.3.5 Information Representation**
- Reliable reconfigurable nano-computing

---

**Roadmap Timeline**
- 2005
- 2010
- 2015

---

*Draft*
### Capability 16.3 Intelligent Systems Roadmap

<table>
<thead>
<tr>
<th>16.3 Intelligent Systems (capabilities)</th>
<th>“Artificial Muscle”</th>
<th>Lab in a Tea Cup</th>
<th>Self-Healing Materials</th>
<th>“Artificial Skin”</th>
<th>“Artificial Retina”</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>16.3.1 Multi-scale Modeling</strong></td>
<td>Nano-micro interface models DNA-protein interactions, supra-molecular structures (20 nm3)</td>
<td>Nanoscale module models circuits/systems, nano-Spice</td>
<td></td>
<td></td>
<td>Nano CAD</td>
</tr>
<tr>
<td><strong>16.3.2 Multi-scale Manufacturing</strong></td>
<td>Directed bottom-up Artificial muscle</td>
<td>Fully integrated general bottom-up Self-healing materials</td>
<td>Programmable interconnect for material transport 3D lab-on-a-chip</td>
<td>Large array systems Artificial skin</td>
<td></td>
</tr>
<tr>
<td><strong>16.3.3 Interconnectivity</strong></td>
<td>Nanowire routing (irregular layouts) Post-charge signal transfer</td>
<td></td>
<td></td>
<td>Biotic/abiotic interconnections Electrochemical signaling Artificial retina Bio-silicon signaling</td>
<td></td>
</tr>
<tr>
<td><strong>16.3.4 Utilization of Nano Properties</strong></td>
<td>Atomically uniform nanostructures Quantum sensors</td>
<td></td>
<td>Integrated system level reliable nanostructure arrays Metrology and structure self aligning to optical tolerances of 200 picometers</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>16.3.5 Information Representation</strong></td>
<td>Distributed reconfigurable systems</td>
<td></td>
<td></td>
<td>Real Time Diagnosis and Prognosis</td>
<td></td>
</tr>
</tbody>
</table>

| 2020 | 2025 | 2030 |

---

Draft
## Crosswalk

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<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 pharma-ceuticals</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

Lunar and Mars Robotics Precursor

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

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)

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)

2005

2015

2025

2035

Lt. Weight High Strength Structures

Low Power Avionics

Lightweight, High Efficiency Electrical Power Systems (Solar Arrays, Regenerative Fuel Cells)

Mars robotic missions (every 2 years)

Humans to Mars

Lunar and Mars Robotics Precursor

“Planetary Aircraft” (e.g. Mars)

High Altitude Long Endurance Aircraft

1st Generation Zero Emissions Aircraft

Radiation Protection, Advanced TPS

Lightweight Fuel Tanks, Radiators (Nuclear Prop.)

High Strength/Multifunctional Structures

Sun-Earth Observing Constellations

Large, lightweight highly stable optical and RF apertures and metering structures (~10m)
Nanotechnology Top Level Capability Roadmap (Exploration)

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

Radiation Protection, Advanced TPS

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.)

Humans to Mars
• High Strength/ Multifunctional Structures

Lunar and Mars Robotics Precursor

Capability Roadmap 16: Nanotechnology

16.1 Nano-Structured Materials
• Nanocomposite with 5000X lower permeability
• High Temp Nanomaterial TPS w/50% lower mass
• Flexible, ultralow density insulation
• Nanomaterial fuel cell MEA with 50% higher power density
• High Specific Power Storage
• Nanomaterial based active radiation protection

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
• Lab-in-a Cup
• “Artificial skin”

16.3 Intelligent Integrated Systems
• Nanostructures based sources and detectors
• Arrayed Lab-on-a-chip
• Lab in a Tea Cup
• Self-Healing Materials

2005  2010  2015  2020  2025  2030

– Draft –
Nanotechnology Top Level Capability Roadmap (Science)

**Capability Roadmap 16: Nanotechnology**

- **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)**

**Robotic Missions to Extreme Environments After Mars**
- **(Outer Solar System, Venus ...)**

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

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

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

**Sun-Earth Observing Constellations**

**Very Long Baseline Interferometry**
- **(Planetary Imaging)**

**Large Scale Interferometry**
- **(Planetary Finding)**

---

### 16.1 Nano-Structured Materials
- **Composite Cryotanks**
- **High Temp. Nanomaterial TPS with 50% lower mass**
- **High Specific Power Storage**
- **Improved Efficiency, Durable, Deployable PV Arrays**
- **Reduced Mass, Efficient, Passive Thermal Control**

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

---

**2005 2010 2015 2020 2025 2030**

---

*Draft*
Nanotechnology Top Level Capability Roadmap (Aeronautics)

16.1 Nano-Structured Materials
- Nanocomposite with 5000X lower permeability
- Nanotube wires with 10X higher conductivity than Copper
- 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

1st Generation Zero Emissions Aircraft
- Lt. Weight High Strength Structures
- Low Power Avionics

High Altitude Long Endurance Aircraft

“Planetary Aircraft” (e.g. Mars)

- 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 losing content -- nanotechnology affects many aspects of all other capability areas
  - Clearly show projection into 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>Nanotechnology Crosswalk (Space)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High Energy Power and Propulsion</td>
</tr>
<tr>
<td></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>
</tr>
<tr>
<td></td>
<td>In-Space Transportation</td>
</tr>
<tr>
<td></td>
<td>Advanced high strength, lightweight structural materials</td>
</tr>
<tr>
<td></td>
<td>Advanced Telescopes and Observatories</td>
</tr>
<tr>
<td></td>
<td>Lightweight, high stiffness, low CTE materials for optics and large structures, thermal coatings….</td>
</tr>
<tr>
<td></td>
<td>Robotic Access to Planetary Surfaces</td>
</tr>
<tr>
<td></td>
<td>Lightweight thermal protection</td>
</tr>
<tr>
<td></td>
<td>Human Planetary Landing Systems</td>
</tr>
<tr>
<td></td>
<td>Health monitoring, diagnosis; membranes for life support processes (e.g. air purification, catalysis), radiation protection…</td>
</tr>
<tr>
<td></td>
<td>Human Health and Support Systems</td>
</tr>
<tr>
<td></td>
<td>Sensors, electronics, materials (light weight, high strength; high thermal conductivity; radiation protection; self-healing,…)</td>
</tr>
<tr>
<td></td>
<td>Human Exploration Systems and Mobility</td>
</tr>
<tr>
<td></td>
<td>Autonomous Systems &amp; Robotics</td>
</tr>
<tr>
<td></td>
<td>Low power computing and electronics; systems for sub-kg rovers</td>
</tr>
<tr>
<td></td>
<td>Scientific Instruments and Sensors</td>
</tr>
<tr>
<td></td>
<td>Ultra-sensitive, environmentally robust detectors; compact active sources (laser, X-ray, sub-mm); high temperature IR detectors…</td>
</tr>
<tr>
<td></td>
<td>In-Situ Resource Utilization</td>
</tr>
<tr>
<td></td>
<td>Process monitoring sensing, catalysis and filtration</td>
</tr>
<tr>
<td></td>
<td>Communications and Navigation</td>
</tr>
<tr>
<td></td>
<td>Advanced low power electronic and photonic devices and systems</td>
</tr>
<tr>
<td></td>
<td>Transformational Spaceport/Range</td>
</tr>
<tr>
<td></td>
<td>Sensing for environmental monitoring</td>
</tr>
<tr>
<td></td>
<td>Advanced Modeling Simulation &amp; Analysis</td>
</tr>
<tr>
<td></td>
<td>Multi-scale modeling for materials, devices and systems</td>
</tr>
<tr>
<td></td>
<td>Systems Engineering Cost/Risk Analysis</td>
</tr>
<tr>
<td></td>
<td>TBD</td>
</tr>
</tbody>
</table>

– Draft –
### Nanotechnology Crosswalk (Aero)

<table>
<thead>
<tr>
<th>Area</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Energy Power and Propulsion</td>
<td>Very high efficiency PV, electrodes for advanced batteries, actuators, motors, fuel cell membranes and lightweight tanks</td>
</tr>
<tr>
<td>Airframe (Transportation)</td>
<td>Advanced high strength/stiffness, lightweight structural materials</td>
</tr>
<tr>
<td>Autonomous Systems</td>
<td>Low power computing and electronics</td>
</tr>
<tr>
<td>Advanced Modeling Simulation &amp; Analysis</td>
<td>Multi-scale modeling for materials, devices and systems</td>
</tr>
<tr>
<td>Systems Engineering Cost/Risk Analysis</td>
<td>TBD</td>
</tr>
</tbody>
</table>

A high degree of commonality between aeronautics and space applications

Impact:

- **Highest**
- **Next Highest**
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

- 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?
Mature, Proven but Bounded Technology

“Old-Guard” Technology

Technology Limits

New, Unproven but “Unbounbded” Technology

“New Era” Technology

Mission Needs

Oops! Maybe We Should Work Together.