Capability 9.1
Exploration

Presenters: Rick Eckelkamp, Team Coordinator
Jim Blacic
9.1 Exploration Activities
Exploration Challenge

- To build an efficient, cost effective exploration infrastructure,

- To coordinate exploration robots & crews from multiple earth sites to accomplish science and exploration objectives, and

- To maximize self-sufficiency of the lunar/planetary exploration team.
The challenge is to preserve exploration and science participation by essential Earth-based personnel within the new context of an operationally efficient, crew-centered system.

Efficiency and safety concerns dictate heavy use of automation and robots working in cooperation with humans.

This summary pitch and the appendix material outline the capabilities required to accomplish these objectives.
Capability Breakdown Structure

9.1 Exploration

9.1 Exploration Activities

- 9.1.1 Physical Access to Exploration Targets
- 9.1.2 Observation
- 9.1.3 Analysis
- 9.1.4 Operate
- 9.1.5 Command and Control Information

More details for all sections are given in the Appendix.
Drivers/Assumptions for Exploration

- Lunar missions will develop the capabilities to send humans to Mars (hence must be of long duration, > 6 months)
- Scientific exploration will require:
  - Advanced sampling techniques (surface and subsurface)
  - Analytical capability available on the Moon and Mars
  - Global access
- Power will be readily available (100s of KW available to bases)
- Communications – very high bandwidth will be provided at least locally
- Crew will need rapid access to large databases for both exploration and maintenance
- Robotic devices must be capable of significant autonomous operation
- Environment protection will be available for radiation (including solar flares), dust, and other environmental hazards on the Moon and Mars
This sub-team treats three integrated themes:

- What are the required elements/tools of lunar/planetary field science and field exploration? (9.1 - 9.3)
- What kind of operational issues need to be addressed for exploration efforts? (9.4)
- What are the associated elements of a command and control system? (9.5)

Exploration Sub-team Goals:

- Identify specific capabilities (hardware, software, techniques, and processes) that must be developed to achieve successful exploration.
- Outline operations trades to accomplish exploration in an efficient and affordable manner.
Earth-based control of multiple reconnaissance robots
Earth-based control of teams of infrastructure-building robots
Astronauts arrive and work in cooperation with robots.
- Building infrastructures
- Exploring
- (Astronauts’ stays start with days; then, proceed to months)
The surface base comes online.
Remote site sorties begin, supported by surface base.
The Capabilities presented herein are in the context of conducting lunar/planetary remote work missions with the following profile:

- Earth-based operations performing strategic planning and on-call in-depth failure and contingency analysis
- A permanent lunar/planetary base staffed with a large crew performing surface and remote site support functions
- Field EVA personnel performing tasks at one or more remote sites
  - 3-4 crew per site, staying for up to two weeks
  - Remote crew housed in pressurized crew mobile unit with normal background radiation protection (rapid surface transport & early warning high radiation warning system assumed)
  - Substantial highly-automated operational capabilities in addition to rovers and robotic assistants
  - Automated mobile units can be sent to an unstaffed site ahead of the crew
  - Crew arrival via high-speed transport
- Missions are assumed to be as self-sufficient as possible.
  - Lunar Missions Operations are analogues for Mars Mission Operations
Exploration Mission Context

Sub-Orbital Transport

Permanent Base

Crew Transport

Worksite
Capabilities in most need of development:

- Early teleoperated or equivalent machine(s) to construct large trenches for habitat “cut and cover” and to move dirt in general

- Drilling and subsurface sampling at depths beyond 1 m

- Other advanced planetary science tools and techniques

- Multi-sensor field exploration robots, human assistant robots, and other construction robots

- Robust space-qualified computers and advanced operational software

- Robust human exploration operations control architecture
9.1 Exploration Summary Roadmap

**Key Assumptions:** Human Exploration of Moon & Mars

- **2008 Lunar Orbiter**
- **2008 CEV Test Flight**
- **2010 Recon Robots at the Moon**
- **2012 Robotic Infrastructure Building Begins**
- **2014 CEV LEO**
- **2015 Initial Human Presence**
- **2017 ISRU Production Starts**
- **2020 Long Term Human Lunar Presence**

**Reconnaissance Tools/Robots**
- **2008** Orbital, Robot Rovers
- **2008** Orchestration
- **2010** Surface Resource
- **2011** Subsurface Structure
- **2015** Prospecting Fields Selection
- **2016** Deep Drilling
- **2020** Remote Site Science Tools online

**Sample Collection Tools/Robots**
- **2008** Trenching
- **2008** Operations
- **2010** Shallow Drilling
- **2010** Advanced Software Capability

**Infrastructure Tools/Robots**
- **2008** Trenching
- **2008** Operations
- **2010** Shallow Drilling
- **2010** Advanced Software Capability

**Operations Advanced Software Capability**
- **2007** Trajectory Design
- **2008** FDIR 1 Planning
- **2009** FDIR 2 Planning
- **2011** Re-planning, Contingency Analysis
- **2012** FDIR 3 Planning
- **2015** On-surface Training
- **2017** FDIR 3 Planning
- **2020** Field Science Data & Execution Support

**Command and Control Infrastructure**
- **2008** Initial Centers online for vehicle & robotic control
- **2009** First draft of centers’ process and functional allocation trades
- **2011** Inter-control center systems data sharing & backup for systems/robotic control
- **2015** Inter-control center shared planning & re-planning
- **2019** US control centers connect to international control centers

**Essential Command and Control Support Infrastructure Development**
- **2005** First draft of centers’ process and functional allocation trades
- **2006** C&C functional allocation trades operational plan in place
- **2009** U.S. distributed C&C finalized

**Distributed Command and Control Process Development**
- **2005** First draft of centers’ process and functional allocation trades
- **2006** C&C functional allocation trades operational plan in place
- **2011-2015** International C&C plan development

- **2012 – 2016** Initial surface navigation and communication beacon deployment
- **2017 – 2020** High bandwidth surface base communication system deployment

**Major Decision**
- **2005**
- **2010**
- **2015**
- **2020**

**Major Event / Accomplishment / Milestone**
- **2008 Lunar Orbiter**
- **2008 CEV Test Flight**
- **2010 Recon Robots at the Moon**
- **2012 Robotic Infrastructure Building Begins**
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Due to yearly budget pressures, NASA has historically concentrated mostly on vehicle hardware development and low initial costs.

The focus has not been on providing efficient operational systems that would lower total lifetime costs.

As a result, high operations costs have prevented NASA from sponsoring many worthwhile programs.

A sustainable exploration program should allocate funds from the onset to develop an efficient operational exploration system.

Besides saving money, an efficient operational system will be essential for Mars operations.
Additional Detail 9.1 Exploration
9.1.4
Operate

9.1
Exploration Activities

9.1.4
Operate

9.1.4.1
Plan/Re-Plan

9.1.4.2
Setup/Teardown

9.1.4.3
Train

9.1.4.4
Perform

9.1.4.5
Recover

9.1.4.6
Maintain

9.1.4.7
Document
9.1.4 Operate

- **Description:**
  - “Operate” is the full-life cycle of an activity from concept to close-out for Assembly, Science and Exploration.

- **The crew performs Exploration Activities to:**
  - Study geologic features
  - Explore for resources
  - Install scientific equipment
  - Conduct engineering activities
  - Explore the environment
9.1.4 Operate

- The Crew/System must operate these activities in a self-sufficient manner
  - Plan/Replan
  - Setup/Teardown
  - Train
  - Perform
  - Recover
  - Maintain
  - Document
9.1.4.1
Plan/Replan (Surface IVA/Earth)

- **Description:**
  - Define missions, suites of activities
  - Perform pre-mission contingency analyses
  - Construct trajectory profiles, activity timelines, automated process scripts, supporting data
  - **Examples:**
    - On-board crew activity scheduler/resource planner
    - Robotic failure contingency planning

- **Benefits:**
  - Ability to manage activities against limited resources (power, time, consumables, etc).
  - Identify significant contingent plans (strategic/tactical)

- **Figures of Merit:**
  - Number of crew tasks done in a work day; rate of resource use; number of planning personnel

- **General Assessment:**
  - Mostly manual processes requiring many personnel; no off-earth capability; promising partial prototypes exist

- **Development Required:** Medium
9.1.4.2
Setup/Teardown (EVA/IVA)

- **Description:**
  - Identify areas of exploration
  - Deploy tools/support equipment and consumables
  - Tear-down and retrieve equipment, pack samples
  - **Examples:**
    - Deploy navigation/communications surface beacons
    - Robots prepare in-space EVA site before crew egresses
    - Robotic planetary surface reconnaissance

- **Benefits:**
  - Timely preparation for exploration activities, use of robots increases crew EVA efficiency

- **Figures of Merit:**
  - Amount of crew EVA time and resources needed, number of parallel activities accomplished per unit time

- **General Assessment:**
  - Some planetary & ISS robotic successes, more progress needed in robot autonomous activity control

- **Development Required:** Medium
**9.1.4.3 Train (IVA/Earth)**

- **Description:**
  - Preparing for an activity by practicing activities using equipment and/or computer models, virtual reality (VR), etc.
  - **Examples:**
    - On-board “just-in-time” training for science activities
    - Planetary surface system refresher training
    - Human tele-robotic robot training
    - Inter-robot task training transfer

- **Benefits:**
  - Ability to familiarize the crew with work processes and practices, efficient training of robots

- **Figures of Merit:**
  - Time required to train crew and robots, ability to field new equipment & experiments without requiring crew training on Earth

- **General Assessment:**
  - 1&2) NSTS & ISS have some onboard training devices; ground-based VR training exists; 3) tele-robot training used in some industries; 4) robot-to-robot training in experimental stage

- **Development Required:** 1 & 2 – **Low**; 3 & 4 - **Medium**
9.1.4.4
Perform (EVA/IVA)

- **Description:**
  - To perform the activity that has been planned
  - Crew or robots using a repertoire of software aids, hardware tools, and vehicles
  - **Examples:**
    - Automatic execution of scripted robotic activity plans
    - Surface-based resource planner
    - Crew Situational Awareness System
    - Robust data access systems for the EVA crew

- **Benefits:**
  - Actual achievement of science and exploration goals

- **Figures of Merit:**
  - Time to achieve activity completion per task; ability to manage multiple tasks at the same time; situational understand of the Crew about the activity; safety of the Crew during EVA/IVA

- **General Assessment:**
  - Tightly managed schedules and processes for most activities, Single sequential activities are the norm. Situational Awareness and Multi-modal interfaces limited.

- **Development Required:** Medium
9.1.4.5
Recover (EVA/IVA)

• **Description:**
  – To be able to adapt to a change in the activity or equipment status
  – To be able to implement backup/contigencies in a time-critical fashion
  – **Examples:**
    • Human and system health monitoring, fault detection, and reconfiguration
    • Invocation of contingent plans

• **Benefits:**
  – To continue an activity in the presence of changing requirements, system health, and environmental conditions.
  – Identify significant contingent plans (tactical/immediate)
  – Improves safety to systems and crew

• **Figures of Merit:**
  – Time to diagnose a problem, and modify plan accordingly

• **General Assessment:**
  – After-the-fact analysis is very robust; Real-Time Systems Health Management is limited by the on-board sensing capability (weight and power concerns). Caution and warning events require human expertise to resolve. Inflexible recovery schemes (typically scripted failover to backups).

• **Development Required:** High
9.1.4.6
Maintain (EVA/IVA)

- **Description:**
  - To perform needed support, reconfiguration or repairs
  - **Example:**
    - On-line documentation, procedures, manuals, videos
    - Embedded sensors for health management

- **Benefits:**
  - Ability to repair a defective system in-the-field
  - Reduced maintenance costs through adoption of condition-based maintenance policies
  - Faster turnaround of reusable systems

- **Figures of Merit:**
  - System down time; logistics required to maintain operations; Human intervention time required; # of replacements vs repairs required

- **General Assessment: Informed Logistics:**
  - Limited built-in troubleshooting aids in components and subsystems.
  - Condition-based maintenance (instead of fixed schedules) gaining ground in DoD and commercial aviation.
  - Early investigations into prognostics (notably JSF and 777).

- **Development Required: High**
Description:
- To capture and record the results of activities that are occurring (or have occurred)
  - Examples:
    - Automated Audio/visual capture and information linkage of Crew state and samples
    - Intelligent telemetry documentation
    - Spoken language recording/recognition

Benefits:
- Ability to share the Full context and record of all scientific and explorations activities;
  Ability for the Crew to stop and restart activities efficiently

Figures of Merit:
- % of the information and context recorded for every Exploration activity; time needed to understand what occurred in the activity by a 3rd party

General Assessment:
- Current SOA in space is recorded voice and video loops; manual digital pictures;
  Automated context recording systems are in initial development. Limited

Development Required: Medium - High
## Maturity Level – Capabilities for 9.1.4 Operate

<table>
<thead>
<tr>
<th>Capability / Technology</th>
<th>SOA</th>
<th>TRL</th>
<th>Needs</th>
<th>Need TRL 6</th>
<th>Capability Date</th>
<th>CRL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>9.1.4.1 Plan/Re-Plan.</strong></td>
<td>Ground-based: Timeplanner, MAPGEN, SPIFE</td>
<td>6</td>
<td>An on-board capability to plan activities and schedules against resources / time</td>
<td>2005</td>
<td>2010</td>
<td>5</td>
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<tr>
<td><em>Key Tech: Crew-centered tactical planning and adaption</em></td>
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<tr>
<td><strong>9.1.4.2 Setup/Teardown</strong></td>
<td>Automated Bulldozers, Unfolding tents</td>
<td>3</td>
<td>Cooperative automation assembling and constructing systems</td>
<td>2009</td>
<td>2014</td>
<td>2</td>
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<tr>
<td><em>Key: Automated construction and site preparation</em></td>
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<tr>
<td><strong>9.1.4.3 Train</strong></td>
<td>ISS systems; Military systems</td>
<td>5</td>
<td>VR and Multimodal portable training system. Human factors</td>
<td>2008</td>
<td>2012</td>
<td>5</td>
</tr>
<tr>
<td><em>Key: Just-in-time training for Crew while in field</em></td>
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<tr>
<td><strong>9.1.4.4 Perform</strong></td>
<td>Hubble repair; N/A</td>
<td>3</td>
<td>EVA Crew and Robotics coordinating together and with ground on common tasks</td>
<td>2009</td>
<td>2014</td>
<td>2</td>
</tr>
<tr>
<td><em>Key: Coordinated human automation interaction</em></td>
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<tr>
<td><strong>9.1.4.5 Recover</strong></td>
<td>Ground-based after the fact.</td>
<td>5</td>
<td>Prognostic and onboard diagnosis and health management</td>
<td>2007</td>
<td>2010</td>
<td>4</td>
</tr>
<tr>
<td><em>Key: Systems being able to gracefully degrade and reconfigure</em></td>
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<tr>
<td><strong>9.1.4.6 Maintain</strong></td>
<td>RFID, and military</td>
<td>5</td>
<td>Design and Logistics for Maintenance and common parts</td>
<td>2007</td>
<td>2010</td>
<td>4</td>
</tr>
<tr>
<td><em>Key: In-situ repair and support of systems</em></td>
<td></td>
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<tr>
<td><strong>9.1.4.7 Document</strong></td>
<td>Video, and Audio clips</td>
<td>5</td>
<td>Focus at depth Volatile capture mechanism</td>
<td>2007</td>
<td>2012</td>
<td>4</td>
</tr>
<tr>
<td><em>Key: Automatically capturing the complete record of all Crew and system actions</em></td>
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9.1.5
Command and Control & Information

9.1
Exploration Activities

9.1.5
Command and Control & Information
9.1.5 Command and Control

- **Description:**
  - To control the timing and execution processes of exploration activities
  - Includes communication, procedural, software, and process methods
  - **Examples:**
    - Lunar/planetary surface robot control
    - Communications reconfiguration
    - Sharing of exploration data among control centers

- **Benefits:**
  - Provides essential operational infrastructure that enables accomplishment of mission objectives

- **Figures of Merit:**
  - number of ground personnel required to:
    - control and plan operations and
    - maintain operational capabilities
  - cost per accomplished exploration objective
  - number of exploration objectives met

- **Development Required:** Medium to HIGH
To have a successful and flourishing exploration program, we must make a “Earth-shaking change” in how we perform command and control.

- From ground-centered control to crew-centered control

- “They that begin a program with a large marching army continue that program with a large marching army.”

- Sheer economics and competition demand this change.
From today’s ground-centered concept of Command and Control to a Crew-centered concept of Control

Mission Management Systems
- Routine systems management
- Anomaly response and recovery
- Vehicle & mission level awareness

Human-automation interaction
- Adaptive decision support
- Situation awareness displays
- Crew Caution & Warning alerts

Robotic Systems Management
- Human-machine multi-agent coordination
- Real-time activity planning and sequencing

Networked Communication Infrastructure
- Adaptable Communications to bring information to/from the Crew
Apollo Operations Model:
- All in-space activities managed by Ground Control
- All ground-space communication through Cap Com
- Minute-by-minute crew activity plans made on ground
- Voice-loops to Earth were critical
- Life-support, spacecraft health, and navigation were all managed from Mission Control
- Large Launch, Mission Control, and Science Teams
- Post launch ground operations, divided by areas, were located in one place
- Still used by all Space Agencies today
The Goal: Crew-Centered Operations

Crew-Centered Operations:
- All in-space activities managed by crew
- Long range planning performed by ground
- Short term planning and replanning performed by crew
- High degree of in-space fault recovery without ground
- Constant voice-loops to Earth are non-critical.
- Life-support, spacecraft health, navigation are all managed by crew and on-board systems.
- Launch, Mission Control, and Science Teams are “On-Call”; they have other critical jobs.
- Realtime mission control team is small - more like a “Mission Support Line”

In-Space crew Ops are Strategically Planned by Earth but tactically operated by the crew On-board systems

Launch Operations: <200? People

Ground Control Ops: 20 People; 300 on-call

Science Operations: many scientists distributed worldwide

Earth Orbit Ops Managed by Crew and On-board systems

Abort Capacity

Crew Launch

Earth Return

Crew Transfer

Robotic Ops are Dynamic and Managed by Crew or ground

Lunar Ops are dynamically determined from basic plans by Crew and On-board systems
Mission Control becomes Mission Support

**Distributed ground-flight support is the communication lifeline between crew, robotics, and earthbound operations.**

- The crew needs to
  - Perform scientific and engineering activities, and
  - Be at the center of command and control activities
  - Manage in-space facilities
  - Manage deployment of scientific/engineering equipment
- The ground is the support to enable this to happen.
<table>
<thead>
<tr>
<th>Robotic Control</th>
<th>Earth</th>
<th>Surface Base</th>
<th>Field</th>
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</thead>
<tbody>
<tr>
<td>Telerobotic Commanding</td>
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<tr>
<td>Single-Joint</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Coordinated Multi-Joint</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Scripted Control</td>
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<tr>
<td>Hand-Built Script Writing</td>
<td>Prime</td>
<td>Backup</td>
<td>No</td>
</tr>
<tr>
<td>Training-Method Script Writing</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Script Execution</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Voice/Visual Commanding</td>
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<tr>
<td>Single/Multi-Joint Commanding</td>
<td>No</td>
<td>Backup</td>
<td>Prime</td>
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<tr>
<td>Auto-Sequence Control</td>
<td>Backup</td>
<td>Shared</td>
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<tr>
<td>Higher-Level Task Initiation</td>
<td>Backup</td>
<td>Shared</td>
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<tr>
<td>Autonomous Operations Monitoring</td>
<td>Backup</td>
<td>Shared</td>
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<tr>
<td>Reconnaissance Robot Control</td>
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<tr>
<td>Long Duration</td>
<td>Prime</td>
<td>Backup</td>
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<td>Short Duration</td>
<td>Backup</td>
<td>Prime</td>
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<tr>
<td>Field Robot Crew Assistant Control</td>
<td>No</td>
<td>Backup</td>
<td>Prime</td>
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## Crew Operations Support

<table>
<thead>
<tr>
<th>Crew Operations Support</th>
<th>Earth</th>
<th>Surface Base</th>
<th>Field</th>
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</thead>
<tbody>
<tr>
<td><strong>Activity Planning</strong></td>
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<tr>
<td>Yearly/Monthly Planning</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
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<tr>
<td>Contingency Planning</td>
<td>Yes</td>
<td>No Prime</td>
<td>No Support</td>
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<tr>
<td>Weekly Planning</td>
<td>No</td>
<td>Prime Shared</td>
<td>Shared Prime</td>
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<tr>
<td>Daily Planning</td>
<td>No</td>
<td>Shared Backup</td>
<td>Prime</td>
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<tr>
<td>Detailed Activity Schedule Building</td>
<td>No</td>
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<tr>
<td><strong>Daily Activity Monitoring</strong></td>
<td>No</td>
<td>Support</td>
<td>Prime</td>
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<tr>
<td><strong>Systems Monitoring</strong></td>
<td>On-Call Expertise</td>
<td>Support</td>
<td>Automated</td>
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<tr>
<td><strong>System Failure Analysis and Reconfiguration</strong></td>
<td>On-Call Expertise</td>
<td>First Aid</td>
<td>Support</td>
</tr>
</tbody>
</table>
To accomplish efficient operations and control requires:

- Substantial advances in some areas of autonomous systems, robots, and robotic control,

- Development of methods to perform crew-centered and integrated robot-human operations, and

- Space communications and computer structures that enable multiple Earth-based control centers to:
  - control lunar/planetary robots,
  - perform inter-center voice, data, and video exchanges
  - perform integrated command and control of in-transit and lunar/planetary operations.
<table>
<thead>
<tr>
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<th>Capability Date</th>
<th>CRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order of magnitude faster computers</td>
<td>1800+ MIPS rad. hardened</td>
<td>5</td>
<td>Space qualify, upgradeable</td>
<td>2007</td>
<td>2009</td>
<td>4</td>
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<tr>
<td>Large distributed data bases</td>
<td>Exist today</td>
<td>9</td>
<td>Populate with exploration data</td>
<td>n/a</td>
<td>2011</td>
<td>5</td>
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<tr>
<td>100 MBPS space comm link</td>
<td>1 MBPS</td>
<td>2</td>
<td>Space qualify, upgradeable</td>
<td>2012</td>
<td>2015</td>
<td>2</td>
</tr>
<tr>
<td>Web-based/similar space network</td>
<td>Earth equivalent exists today</td>
<td>4</td>
<td>Space qualify, upgradeable</td>
<td>2009</td>
<td>2012</td>
<td>3</td>
</tr>
<tr>
<td>Inter-control center voice, data, video</td>
<td>Essentials in-place today</td>
<td>8</td>
<td>Upgrade protocols</td>
<td>n/a</td>
<td>2008</td>
<td>5</td>
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<tr>
<td>Advances in ground-based robotic control</td>
<td>ISS rudimentary, Robonaut demo, MER control</td>
<td>2</td>
<td>Fast comm link, time delay abatement s/w</td>
<td>2008</td>
<td>2010</td>
<td>3</td>
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<tr>
<td>Autonomous FDIR</td>
<td>NSTS, various fighter jets, deep-space probes, Freedom ISE</td>
<td>4</td>
<td>Inter-system FDIR, AI trend analysis advances</td>
<td>2008-2012</td>
<td>2010-15</td>
<td>3</td>
</tr>
</tbody>
</table>
9.1 Exploration Activities

9.1.1 Physical Access to Exploration Targets

9.1.2 Observation

9.1.3 Analysis

9.1.4 Operate

9.1.5 Command and Control Information

More details for all sections are given in the Appendix
9.1.1 Physical Access to Exploration Targets

9.1 Exploration Activities

9.1.1 Physical Access to Exploration Targets

9.1.1.1 Sample Collection

9.1.1.2 Trenching

9.1.1.3 Drilling
9.1.1.1 Sampling

Description – Physical acquisition of planetary solid, liquid or gaseous materials for scientific/engineering characterization or ISRU assessment

Benefits – Enables more accurate, precise and complete characterization of planetary materials than can be done in the field or in situ. Creates archive for future study by a larger body of investigators

FOM – Mass, volume, degree of contamination

General Assessment – solid sampling is adequate; gas/liquid technology is inadequate

Development Needed -- Medium
9.1.1 PHYSICAL ACCESS TO XPLORATION TARGETS

9.1.1.2 Trenching

Description – Removal of planetary solid material to produce a linear space with vertical or sloping faces that exposes the subsurface for
a) sampling or *in situ* observation
b) placement of habitat modules
c) placement of utility conduits

Benefits – Exposes near-surface planetary materials for scientific investigations. Enables mass-efficient shielding of habitats or utility conduits by “cut and cover”

**FOM** – length, width, depth; time to construct

**General Assessment** – shallow trenching is adequate; deeper/longer trenching is inadequate

**Development Needed** – a) Medium; b) High; c) Medium
**9.1.1.3 Drilling**

**Description** – Removal of planetary solid material to produce a cylindrical hole and core of material. Used for depths beyond the capability of trenching.

- **Near-surface**: 10-100 cm in loose soils and 1-10 cm in hard rock
- **Shallow**: 10 cm – 10 m in all rock types
- **Intermediate**: 10 m - ~300 m in all rock types
- **Deep**: Beyond ~ 300 m in all rock types

**Benefits** – Exposes the planetary subsurface for scientific investigations and discovery; production of resources such as ground water

**FOM** – % retrieval of cuttings or core; degree of contamination

**General Assessment** – a) & b) prototypes under development; c) & d) = TRL 1

**Development Needed** --a) = Low; b) = Med; c) = High; d) = High
### 9.1.1 Physical Access to Exploration Targets

<table>
<thead>
<tr>
<th>Capability /Technology</th>
<th>SOA</th>
<th>TRL</th>
<th>Needs</th>
<th>Need TRL 6</th>
<th>Capability Date</th>
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<tr>
<td><strong>9.1.1.1 Sampling</strong></td>
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<td>(a) Solid (regolith)</td>
<td>Apollo</td>
<td>9</td>
<td>Retain volatiles; top-most layer of surface</td>
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<td>Key: sealing; cryogenic sample handling</td>
<td>Viking</td>
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<td>(b) Liquid (ground water)</td>
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<td>1</td>
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<td>(c) Gas (volatiles, atmosphere)</td>
<td>Viking</td>
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<td>Natural-state acquisition / Handling</td>
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<tr>
<td>(a) Sampling Trench</td>
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<td>9</td>
<td></td>
<td>-</td>
<td>2008</td>
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<td>Key: Scooping tools</td>
<td>Viking</td>
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<td>MER</td>
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<td>(b) Habitat Trench</td>
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<td>2,2</td>
<td>Equipment development; explosives technique/materials development</td>
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<td>Key: Big “back hoe”, explosives</td>
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# Physical Access to Exploration Targets

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<th>Capability Date</th>
<th>CRL</th>
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<td>(c) Utility Trench</td>
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<td><strong>Key: Powered trencher</strong></td>
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<td>9.1.1.3 Drilling</td>
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<td>(a) Near-surface</td>
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<td>(b) Shallow</td>
<td>Lab</td>
<td>3,3</td>
<td>Prototype testing in relevant environment; core acquisition development</td>
<td>2007</td>
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<td>2,2</td>
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<td>(d) Deep</td>
<td>Terr.</td>
<td>2,2,2</td>
<td>Prototype development and testing; well completion development</td>
<td>2018</td>
<td>2025</td>
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</tbody>
</table>
9.1 Exploration Activities

9.1.2 Observation

9.1.2.1 Orbital/Aerial Remote Sensing

9.1.2.2 Surface Sensing

9.1.2.3 Subsurface Remote Sensing

9.1.2.4 Surface Outward Observation
9.1.2 OBSERVATION

9.1.2.1 Orbital /Aerial Remote Sensing

Descriptions -- a) Orbital: planet-wide imaging and sensing of composition, topography, gravity field, magnetic field; b) Suborbital/aerial: Imaging, composition & topography

Benefits – Determine elemental and mineralogic compositions, topography, geophysical fields; enable site evaluations and surface route planning

FOM – % of major/minor rock-forming elements; accuracy; precision; spatial resolution

General Assessment – Current flight instruments generally adequate; improvements in accuracy/precision and spatial resolution needed; suborbital/aerial platforms needed

Development Needed -- a) Low; b) High
9.1.2 OBSERVATION

9.1.2.2 Surface Sensing

9.1.2.2.1 Direct Contact

**Description** – Placement of sensors and/or interrogation energy sources directly in contact with soil or rock surface

- **Passive**: natural energy emanated or reflected from surface and measured in contact; e.g., natural $\gamma$ radiation spectrometer
- **Active**: artificial energy introduced to surface material by contact to produce a characteristic signal measured in contact; e.g., Mossbauer spectrometer

**Benefits** – Maximizes the accuracy and precision of measurement location; minimizes the effects of intervening medium such as an atmosphere; allows more time for signal integration compared to orbital/aerial

**FOM** – Accuracy/precision of major rock-forming elements

**General Assessment** -- Existing flight instruments adequate; some improvement in accuracy and precision needed

**Development Needed** -- a) Low; b) Low
9.1.2 OBSERVATION

9.1.2.2 Surface Sensing

9.1.2.2.2 Stand-Off

Description – Placement of sensors and/or interrogation energy sources at some distance from the surface being interrogated

- **Passive:** Natural energy emanated or reflected from surface and received at a distance; e.g., Vis/IR imaging spectrometer
- **Active:** Artificial energy transmitted to the surface material from a distance to produce a characteristic signal; e.g., laser-induced break-down spectrometer

Benefits – Enables measurement at locations not directly accessible by contact, e.g., cliffs; enables simultaneous, contextual measurement of large areas from a single location

FOM – Accuracy/precision of major rock-forming elements

General Assessment -- Current passive flight instruments adequate; Active instruments inadequate

Development Needed -- a) Low; b) Medium
9.1.2.3.1 Sub-Surface Sensing
Automated Image Processing

Description – Use automated techniques to recognize key surface features in voluminous photographic data sets and to interpolate or extrapolate surface features to probable location of key features below the surface:

- Example A: Exposed rock in steep crater walls shows regolith depth (and resources) that extend to surrounding subsurface areas
- Example B: Breached lava tubes (rilles / “skylights”) locate intact sections under the surface (up to 300 m diameter; many km length)

Benefits

A) Automated location of exposed rock areas and mapping of expected regolith depth will assist plans to bury habitats (trenching).
B) Automated location of lava tubes (natural shelters from radiation, dust, heat, and cold) may avoid energy-intensive trenching operations

FOM – Depth and size of features mapped; accuracy of predictions

General Assessment -- Improves accuracy, consistency, cost (vs. human)

Development Needed -- Medium
9.1.2.3.2 Sub-Surface Sensing
Radiation Interactions

Description – Assess sub-surface minerals by sensing secondary radiation (neutron, gamma ray/X-ray) from natural or artificial primary radiation interactions with subsurface material (up to ~ 1 meter depth).

Artificial radiation sources might potentially be integrated with radioisotope thermal generators (also used for electrical power or heat)

Benefits –
Neutron spectrometers on Lunar Prospector and Mars Observer located hydrogen and water which could have significant value for ISRU.
New instruments may allow rapid operation from a rover on the surface for precise mapping of resources for future human consumables (e.g., frozen H2O and other volatiles), and for propellant production.

FOM – Depth of observation, energy required; accuracy & precision of data

General Assessment – Proven technique, integration with RTG is new

Development Needed -- Low
Sub-Surface Irradiation by "Multi-Mission Radioisotope Thermoelectric Generator"

In development now; 1st flight in ~2009

45 kg; degradation < 22%, 14 yr life

Plutonium Radioisotope Energy Source

Trigger for Secondary Radiation (e.g., neutron & gamma) from Sub-Surface

Information improves understanding of secondary elements via alpha / neutron / gamma / X-ray

Mars Science Laboratory (example use)
Description – Locate features and determine characteristics below the surface by illuminating areas of interest with radar. Radar may help locate key ISRU species (such as thick slabs of ice, which reflect circularly polarized radar with a high reverse circular polarization ratio)

A) Radar from Earth: High power, large apertures, long ranges ($10^6$ km)
B) Radar from Orbit: Intermediate power & aperture, Mid-range ($10^2$ km)
C) Radar on the surface: Low power, small aperture, short range (1 m)

Benefits –
A) Earth Radar finds ice in Mercury’s polar craters (not yet on moon)
B) Orbital Radar (SAR) finds bedrock under dry soil, maybe metal ores (e.g., Chromite / Platinum Group Elements layers in impact melts)
C) Ground Penetrating Radar finds geotechnical features / strata

FOM – Depth of observation, energy required; accuracy & precision of data

General Assessment – Well characterized techniques

Development Needed -- low
Description – High velocity impact vaporizes material from below the surface, allowing spectroscopic observation to determine mineral content (like “LIBS”, but with more energy):

A) Natural impacts (meteoroids)
B) Artificial impacts (penetrators, spacecraft components, explosions)

Benefits – Assesses minerals and resources for future human consumables (frozen H2O and other volatiles) and propellant production

FOM – Knowledge of impact location, Energy used, Degree of contamination
General Assessment – Simple technique needs foresight and coordination
Development Needed -- low
Description – Network of seismic sensors to monitor and interpret surface waves following an impact / explosion on the surface or a “moonquake”

Use new “Spectral Analysis of Surface Waves” technique

Benefits –
• Improve prospects of physical access (e.g., avoid drilling into a subsurface boulder, with blocking and breaking of drill strings)
• Locate voids and deposits of lower density materials (e.g., natural caverns for shelter and condensed volatile deposits for ISRU)
• Potential to identify ice strata that record major comet impacts (and maybe even major Earth impacts) which brought water to the moon

FOM – Instrument mass, energy used; accuracy in lower density deposits

General Assessment -- Transfer geotechnical advances to space

Development Needed -- Medium
Description –
• Generate and focus microwaves via a surface reflector to heat regolith at selected depth(s) (up to ~1 meter)
• Determine composition of released volatiles via spectroscopy (or capture on a cold plate / Quartz Crystal Microbalance)

Benefits –
• Assess location, extent and composition of volatile condensates important for ISRU (water, Argon, etc.) without requiring drilling (thereby reducing time, energy, mass, risk, etc.)
• Microwave beams may also assist in recovery of resources and to sinter lunar regolith and thereby create ISRU-derived structures

FOM – Depth, Instrument mass and energy needs; Accuracy of data
General Assessment – New technique, also beneficial for ISRU processes (suggested by L. Taylor) to sinter lunar regolith and create structures

Development Needed -- HIGH
## 9.1.2 Observation

<table>
<thead>
<tr>
<th>Capability</th>
<th>SOA</th>
<th>TRL</th>
<th>Needs</th>
<th>Need TRL 6</th>
<th>Capability Date</th>
<th>CRL</th>
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<tr>
<td>9.1.2.1 Orbital/Aerial Remote Sensing</td>
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<td>9.1.2.1.1 Orbital</td>
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<td>Key: Hi-res instruments</td>
<td>Mars Odyssey</td>
<td>9</td>
<td>Higher spatial resolution</td>
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<td>Key: Hi-res instruments</td>
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<td>(a) Passive</td>
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<td>Key: Neutron spectrometer, γ spectrometer</td>
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<td>Higher data integration rate; higher accuracy/precision</td>
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<td>(b) Active</td>
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<td>Higher data integration rate; higher accuracy/precision</td>
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### 9.1.2 OBSERVATION

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<td>Key: Vis-IR imaging</td>
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<td>spectrometer</td>
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<td>LANL LIBS</td>
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## 9.1.2.3
### SUB-SURFACE OBSERVATION

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<tr>
<td><strong>9.1.2.3.1 Auto. Image Process.</strong>&lt;br&gt;<em>Key: Recognize surface features and extrapolate/interpolate</em></td>
<td>CalTech JARTool; +human</td>
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<td>Interpolate surface data to subsurface</td>
<td>-x</td>
<td>2008</td>
<td>7</td>
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<td><strong>9.1.2.3.2 Radiation Interaction</strong>&lt;br&gt;<em>Key: Integration with powerful external radiation sources</em></td>
<td>Neutron Detectors: MO&amp;Lunar Prospector</td>
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<td>Accelerate data rate via radiation Source integrated with Power/ Heat</td>
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<td>2008</td>
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<td><strong>9.1.2.3.3 Radar Observations</strong>&lt;br&gt;<em>Key: Short wavelength circularly polarized for thin ice</em></td>
<td>Arecibo &amp; Goldstone</td>
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<td>Higher spatial resolution; Access shadows</td>
<td>2008</td>
<td>2012</td>
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<td><strong>9.1.2.3.4 Impact Observation</strong>&lt;br&gt;<em>Key: Coordinated observation during impact events</em></td>
<td>“Deep Impact” mission</td>
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<td>Coordination with astronomy and Japan’s Lunar-A</td>
<td>x</td>
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<td><strong>9.1.2.3.5 Impact Sensing</strong>&lt;br&gt;<em>Key: Spectral Analysis of Surface Waves</em></td>
<td>Geo-tech uses</td>
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<td>Coordination with astronomy and Japan’s Lunar-A</td>
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<td><strong>9.1.2.3.6 Microwave Beam</strong>&lt;br&gt;<em>Key: Focus at depth, assessment (capture?) of volatiles</em></td>
<td>Ovens on Earth</td>
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<td>Focus at depth Volatile capture mechanism</td>
<td>-x</td>
<td>2008</td>
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</table>
Description:
- The lack of a sensible atmosphere, the extreme stability of the surface, the low (but not too low) gravity, and the nature of its rotation make the lunar surface very useful for observations of objects or phenomena not associated with the Moon itself.

- **Targets of Observations**
  - The Universe
  - The Earth
  - The Sun
  - The space environment and phenomena in the Earth-Moon or Sun-Earth system such as interactions of the solar wind with the geomagnetic field.
  - Various experiments in the fields of physics and biology carried out in special facilities

- These functions may not be primary objectives for Exploration but would become attractive scientific investments as lunar surface capabilities and resources become available.

- The instruments would, for the most part, be described as telescopes in the sense that they would enable observations of distant phenomena.
Advantages of Moon for Astronomy

- **Ultra-high vacuum- effectively no atmosphere**
  - Perfect transmittance; diffraction-limited imaging
  - Dark sky - no scattered light allowing daytime as well as nighttime observing and observing close to the Sun in the sky
  - Cold sky everywhere and very cold surface environments in certain crates with permanent shadowing, allowing radiative cooling of telescopes
  - No wind, allowing simple sunshades and lightweight structures

- **High lunar mass**
  - Enormous moment of inertia permits smooth tracking and easy pointing
  - Low but sensible gravity
    - No co-orbiting debris as with spacecraft
    - Dropped tools and parts easily retrieved; favorable work environment compared to zero-g
  - Mass of the Moon shields farside radiotelescopes from Earth “noise”
    - The farside is the only place in the solar system shielded from Earth interference

- **Slow sidereal rate**
  - Sky sources available continuously for 14 days
    - Long-uninterrupted observation of variable phenomena
    - Long sensor integration times for faint sources

- **Very large-scale instruments may be feasible only on the Moon**
  - Giant filled-aperture telescopes
  - Large baseline interferometers
  - Farside radio receiver arrays with large areal expanse
Disadvantages of Moon for Astronomy (As seen by scientific community)

- Expensive to operate human-tended or -emplaced observatories
  - Robotic soft landers cheaper overall although less capable
  - Dedicated human mission for observatory requires development of robotic cargo lander
  - Telescope itself is an expensive instrument (compared to freeflyer)

- Lack of solar power during lunar night
  - Energy storage solutions for lunar night have large mass (e.g., batteries)
  - Nuclear solutions required
    - RTG for small telescope
    - Reactor for large facility

- High radiation background - increased detector noise

- Day-night cycle limits efficiency of single observatory to 50% (compared to deep-space freeflyer)
  - If 100% of sky must be available 100% of time, 2 observatories required
  - Equatorial observatory sees whole sky but any single portion 50% of the time
  - Polar observatory sees 50% of the sky all the time

- Mobilized dust a concern for mirrors and moving parts over time
9.1.2.4.1 Telescopes with Optical Elements (i.e., mirrors)

9.1.2.4.1.1 Large-Aperture UV/Optical/IR (UVOIR) Telescope
- Search for life and detection of Earth-like planets
- Formation & evolution of the early universe

9.1.2.4.1.2 IR and Sub-mm Interferometers
- Studies of forming and evolved extrasolar planetary systems
- Processes and structure of galactic nuclei and quasars

9.1.2.4.1.3 Optical Interferometer
- Imaging nearby stars
- Validating distance scales in the universe

9.1.2.4.1.4 2-Meter Class UVOIR Telescope for Solar System Studies
- Origin of the solar system
- Properties of small bodies, particularly in the Kuiper Belt
- Dedicated study of Mars with monitoring of atmospheric phenomena

9.1.2.4.1.5 Solar monitor facility
- Solar flare physics and prediction
- Solar interior through helioseismology

9.1.2.4.1.6 Nearside Earth Synoptic Earth Observation Facility
- Continuous monitoring of planetary-scale phenomena
  - Global radiation budget including albedo variation
  - Global climate modeling
  - Geomagnetic storms and aurorae
- Continuous monitoring of LEO and GEO
- Earth surface observation and surveillance
Examples of Observatory Instruments Not Based on Standard Optics

9.1.2.4.2 Radio Telescopes
Low-frequency observations not possible from Earth
Long-baseline interferometer
Shielding from terrestrial radio interference

9.1.2.4.3 Large-Aperture X-ray and Gamma-ray Telescopes
Physics of neutron stars and black holes
Stellar accretion disks

9.1.2.4.4 Solar-terrestrial physics facility
Direct solar wind measurement
Reconnection events in the geotail

9.1.2.4.5 Particle Physics, Cosmology, and Gravitational Waves
Cosmic ray measurements
Neutrino telescope
Gravitational wave detector
Moon-scale particle accelerator using ambient vacuum
Details and Benefits of 9.1.4.1:
Optical Observatory Instruments

- **Description**: Much of the observation of other bodies from the Moon will be done at wavelengths ranging from ultraviolet to far infrared where telescopes having reflective optics can be used.
  - **Examples**:
    - Optical interferometer.
    - Nearside Earth Synoptic Earth Observation Facility.
  - **Benefits**: The Moon is an airless body with an extremely stable surface and a slow sidereal rotation rate in synchronicity with its orbital velocity about the Earth. These characteristics are favorable for a variety of scientific observation and research.
  - **FOM**: Angular resolution; detection sensitivity; available integration time; wide spectrum; environmental stability.
  - **General Assessment**: Sophisticated instrumentation exists in terrestrial observatories and aboard robotic spacecraft. Instruments must be adapted for use in lunar setting. In some cases, this will be easy. In others, challenges exist to operate autonomously and continuously in the lunar environment.
  - **Development needed**: LOW
Details and Benefits of 9.1.4.2: Radio Astronomy

- **Description:** Radiotelescopes and interferometers, particularly those operating at low frequencies can observe the universe in unique ways. Interferometers can be designed with elements on the Moon and on the Earth, providing baselines at solar system scales.

- **Examples:**
  - Low-frequency radiotelescope.
  - Long-baseline Moon-Earth radio interferometer.

- **Benefits:** The Moon is an airless body with an extremely stable surface and a slow sidereal rotation rate in synchronicity with its orbital velocity about the Earth. The lunar farside is the only location in the solar system that is perfectly shielded from terrestrial interference. These characteristics are favorable for a variety of scientific observation and research.

- **FOM:** Angular resolution; detection sensitivity; available integration time; wide spectrum; environmental stability.

- **General Assessment:** Antenna design is a highly advanced art. Adaptation to lunar conditions should present few problems.

- **Development needed:** LOW
Details and Benefits of 9.1.4.3: X-ray & Gamma-ray Telescopes

- **Description**: The lack of an atmosphere on the Moon allows observations of high energy photons using instruments with large throughput.
- **Examples**:
  - X-ray radiotelescope.
  - Gamma-ray radiotelescope.
- **Benefits**: The Moon is an airless body with an extremely stable surface and a slow sidereal rotation rate. The gravity field and extremely stable surface will permit construction of unique instruments for research into the high energies in the electromagnetic radiation from the universe.
- **FOM**: Angular resolution; detection sensitivity; available integration time; wide spectrum; environmental stability.
- **General Assessment**: The design of such telescopes is well understood, but the shipment and assembly of large apertures on the lunar surface will require careful operations. Adaptation to lunar conditions should present few problems.
- **Development needed**: MEDIUM
Details and Benefits of 9.1.4.4: Solar-terrestrial physics

- **Description:** The lack of an atmosphere on the Moon allows direct access to the solar wind. The Moon fortuitously sits at a distance where reconnection occurs in the Earth’s magnetic geotail. Observations at radio frequencies and data from satellite constellations anchored to the Moon can provide 3-dimensional information on the interaction between the solar wind and the geomagnetic field.

- **Examples:**
  - The European Cluster mission.

- **Benefits:** Continuous, long-term observation of the Earth-Sun interactions will permit greater sophistication in modeling the effects of solar events on the Earth’s magnetic field, ionosphere, and climate.

- **FOM:** Continuous monitoring; simultaneous in-situ measurements of the solar field at the Earth.

- **General Assessment:** The technology for making these observations is well in hand.

- **Development needed:** LOW
• **Description:** Gravity wave detectors, very large particle accelerators, neutrino telescopes, and cosmic ray measurements are some of the possibilities for advances in cosmology and high-energy physics using research facilities on the lunar surface.

• **Examples:**
  – LIGO.

• **Benefits:** The lunar surface vacuum and the extreme surface stability allow new designs for research in high-energy physics and relativity.

• **FOM:** Long-term observations; extreme environmental stability; ready availability of vacuum environment.

• **General Assessment:** Lunar research facilities in these fields of study may well take on new forms from similar facilities on Earth. The scale of the facilities may be a challenge.

• **Development needed:** MEDIUM
### 9.1.4: Facilities for Observation from the Moon

<table>
<thead>
<tr>
<th>Capability /Technology</th>
<th>SOA</th>
<th>TRL</th>
<th>Needs</th>
<th>Need TRL 6</th>
<th>Capability Date</th>
<th>CRL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>9.1.4.1 Optical Observatory Instruments</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| (a) Telescope (reflective optics)  
  Key: sensor; optics; data processing; construction; operation | Hubble  | 6   | Adapt to lunar setting; integrate into lunar ops | 2019       | 2025            |     |
| (b) Interferometric arrays  
  Key: Optical fiber networks; precision alignment | Earth facilities | 5   | Space qualification; ops in lunar setting | 2024       | 2030            |     |
| (c) Key:                                                                 |         |     |                                            |            |                 |     |
| **9.1.4.2 Radio Astronomy** |         |     |                                            |            |                 |     |
| (a) Antenna design; data processing  
  Key: Frequency response; detector sensitivity; signal reconstruction | Earth facilities; S/C comm | 6   |                                            | 2019       | 2025            |     |
| (b) Interferometric arrays  
  Key: Element communication; timing precision; ops | Earth facilities | 5   |                                            | 2024       | 2030            |     |
### 9.1.4: Facilities for Observation from the Moon

#### 9.1.4.3 X-ray & Gamma-ray telescopes

- **(a) Optics design; sensor development**  
  *Key: sensor; optics; data processing; construction; operation*  
  - SOA: Chandra; Compton  
  - TRL: 6  
  - Needs: Adapt to lunar setting; integrate into lunar ops  
  - Need TRL 6: 2019  
  - Capability Date: 2025

#### 9.1.4.4 Solar-terrestrial physics

- **(a) Solar telescope**  
  *Key: Long-term, uninterrupted imaging of Sun*  
  - SOA: Earth facilities  
  - TRL: 6  
  - Needs: Adapt to lunar setting; integrate into lunar ops  
  - Need TRL 6: 2019  
  - Capability Date: 2025

- **(b) Array of spacecraft monitoring of solar wind interactions**  
  *Key: Orbital coordination; communication; operations*  
  - SOA: CLUSTER  
  - TRL: 7  
  - Needs: Mission design  
  - Need TRL 6: 2019  
  - Capability Date: 2025

#### 9.1.4.5 High-energy Physics & Cosmology

- **(a) Various research facilities**  
  *Key: Innovative utilization of lunar environment; use of lunar mass (e.g., shielding and neutrino detection)*  
  - SOA: Earth facilities  
  - TRL: 5  
  - Needs: Facility concept and design; construction on Moon  
  - Need TRL 6: 2029  
  - Capability Date: 2035
9.1.3 Analysis

9.1 Exploration Activities

9.1.3 Analysis

9.1.3.1 InSitu Analysis

9.1.3.2 Analysis at Base

9.1.3.3 Sample Curation

9.1.3.4 Sample Transport to Earth
Description:

- Scientific investigations on the lunar surface will require some sort of measurement or characterization of lunar materials.
- Some observations or characterizations can be done on materials where they are found using robotic and/or human observers.
- Some observations are too complex or require too much time for in situ analysis and must be done at the base on selected samples.
- A limited number of special samples will be returned to Earth for curation by NASA and study by scientists around the world. These returned samples must be handled and documented by special procedures in accordance with NASA policy.

Major categories of activity are the following:

- 9.1.3.1 In Situ Analysis
- 9.1.3.2 Analysis at Base
- 9.1.3.3 Sample Curation
- 9.1.3.4 Sample transport to Earth
Details and Benefits of 9.1.3.1: In-Situ Analysis

- **Description**: Measurements and/or observations will be taken at a lunar surface site by teleoperated robots or human/robot field teams.
- **Examples**:
  - Spectral analysis of materials in a geologic formation
  - Measurement of soil compressibility with penetrometer
  - Documentation of geologic context of deposits or formations
- **Benefits**: Analysis tools built into a teleoperated robot allow reconnaissance for planning human traverses to a site of interest; acquire information for decisions in real time where spacesuit constraints limit the time available at the location.
- **FOM**: Ability to extract scientific information at high spatial resolution and high signal-to-noise from object of study; low mass, power, volume
- **General Assessment**: Instruments exist in laboratories and in flight-qualified form. Principal challenge is integration of sensors and data management in mobile platforms for lunar surface environment.
- **Development needed**: LOW
Details and Benefits of 9.1.3.2: Sample Analysis at the Base

- **Description:** In-situ analysis capability will be limited. Some samples deemed scientifically significant will require in-depth study. Analytical capability may be included at the base, subject to limits on mass, volume, technology, and crew time.

- **Examples:**
  - Optical microscopy of prepared geologic thin sections.
  - Elemental analysis by x-ray diffraction.

- **Benefits:** Lab environment permits sample preparation that is impossible in the field. Analysis at the base would facilitate planning scientific excursions, e.g., by allowing informed input by terrestrial support teams. It would provide information for selecting samples to be returned.

- **FOM:** Ability to extract information on chemical composition and physical state at submicroscopic dimensions high accuracy and sensitivity from a sample; low mass, power, volume

- **General Assessment:** Sophisticated instrumentation exists in terrestrial laboratories. Instruments must be adapted for use in lunar setting. In some cases, this will be easy. In others, challenges exist to reduce mass, power, and volume.

- **Development needed:** MEDIUM
Details and Benefits of 9.1.3.3: Sample Curation

- **Description**: Some samples will be determined to have sufficient scientific importance as to be preserved and returned to the Earth for study by the global scientific community (as are the Apollo samples and Antarctic meteorites collected by U.S. expeditions).

- **Examples**:
  - Identification in the field of candidate samples for curation
  - Documented collection of samples for potential curation
    - Establish geologic context through photography, orientation, and location (selenographic coordinates).
    - Appropriate packaging for transport to base
  - Bonded storage at the base under lunar environmental conditions for candidate return samples
  - Analytical capability and communication for consultation to decide which candidates should actually be returned

- **Benefits**: The scientific integrity of returned samples must be preserved through strict adherence to documented collection, storage, and packaging procedures.

- **FOM**: Peer-reviewed configuration control processes acceptable to the scientific community.

- **General Assessment**: Well understood. Must be incorporated into mission requirements.

- **Development needed**: LOW
Details and Benefits of 9.1.3.4: Sample Transport to Earth

- **Description**: While properly documented and executed procedures are necessary to maintain scientific integrity of returned samples, the containers and packaging are also important.
- **Examples**:
  - The number of materials with which scientific lunar samples can come into contact is severely restricted.
  - Sealing containers under lunar vacuum in the presence of dust is challenging, particularly given material restrictions.
  - Containers must be physically robust while lightweight.
  - A variety of containers may be needed to return different types of sample.
  - Containers must be designed to be easily opened in the appropriate terrestrial lab environment where curation will take place (lesson learned from Apollo).
- **Benefits**: The scientific integrity of returned samples must be maintained through strict adherence to documented collection, storage, and packaging procedures.
- **FOM**: Peer-reviewed configuration control of processes and materials acceptable to the scientific community.
- **General Assessment**: Well understood. Must be incorporated into mission requirements.
- **Development needed**: LOW
# 9.1.3: Tools of Measurement & Observation

## 9.1.3.1 In-situ Analysis

<table>
<thead>
<tr>
<th>Capability /Technology</th>
<th>SOA</th>
<th>TRL</th>
<th>Needs</th>
<th>Need TRL 6</th>
<th>Capability Date</th>
<th>CRL</th>
</tr>
</thead>
</table>
| (a) Remote sensing (incl. imaging)  
  *Key: sensor; optics; data processing* | MER | 8 | Adapt to lunar setting; integrate into lunar ops | - | 2010 | 7 |
| (b) Local measure. of physical state  
  *Key: Ops environment* | Apollo, Lunakhod | 1 | Natural-state acquisition / handling; | 2015 | 2030 | 0 |
| (c)  
  *Key:* | | 4,2 | Natural-state acquisition / Handling | 2008 | 2012 | 6 |

## 9.1.3.2 Sample Analysis at Base

<table>
<thead>
<tr>
<th>Capability /Technology</th>
<th>SOA</th>
<th>TRL</th>
<th>Needs</th>
<th>Need TRL 6</th>
<th>Capability Date</th>
<th>CRL</th>
</tr>
</thead>
</table>
| (a) Analytical Instrumentation  
  *Key: Packaging current state of art* | Earth labs; ISS | 9 | | - | 2008 | 7 |
| (b) Sample preparation equipment  
  *Key: safety issues re habitat life support (e.g., dust, oil)* | Earth labs | 2,2 | | 2012 | 2015 | 0 |
### Appendices

<table>
<thead>
<tr>
<th>Outline</th>
<th>Description</th>
<th>Slide #</th>
</tr>
</thead>
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<td>US Manned Space Program Relative Cost</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>US Robotic Space Program Relative Cost</td>
<td>76</td>
</tr>
<tr>
<td>9.1.4</td>
<td>The New Explorers and New Operations</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>Lunar Mission Operations Functional Trade Space</td>
<td>78</td>
</tr>
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<td>9.1.5</td>
<td>Mobility/Hybrid Human/Robotic Control Roadmap</td>
<td>79</td>
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<tr>
<td></td>
<td>Some Lunar Base Need Candidates</td>
<td>80</td>
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<td></td>
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<td>Challenges for Exploration Robotics</td>
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<td>Needed Perception and “Cognition” Advances</td>
<td>85</td>
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</table>
## US Manned Space Program Relative Cost

<table>
<thead>
<tr>
<th>Vehicle Development</th>
<th>Apollo</th>
<th>ASTP</th>
<th>Skylab</th>
<th>NSTS</th>
<th>ISS</th>
<th>Exploration</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Ops Systems Development</td>
<td>High</td>
<td>Low</td>
<td>Moderate</td>
<td>Moderate</td>
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<td>High</td>
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<tr>
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<td>N/A</td>
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<td>?</td>
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<td>Low</td>
<td>Low</td>
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<td>Low</td>
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<tr>
<td>Ops costs/yr.</td>
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<td>High</td>
<td>High</td>
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<tr>
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<td>1</td>
<td>1</td>
<td>38 +</td>
<td>5 +</td>
<td>50 +</td>
</tr>
<tr>
<td>Total program cost</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

- **ISS**: International Space Station
- **NSTS**: National Space Transportation System
- **ASTP**: Apollo-Soyuz Test Project
- **Apollo**: Apollo Program
- **Skylab**: Skylab Program
- **ASTP**: Apollo-Soyuz Test Project
- **ISS**: International Space Station
- **Exploration**: Exploration Program

Associated figures: 9.1.1, 9.1.2, 9.1.3, 9.1.4, 9.1.5
## US Robotic Space Program Relative Cost

<table>
<thead>
<tr>
<th></th>
<th>Viking</th>
<th>Hubble</th>
<th>Pathfinder</th>
<th>MER</th>
<th>Exploration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Development</td>
<td>High</td>
<td>High</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Ops Systems Development</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
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<tr>
<td>Vehicle Sustaining Eng./yr.</td>
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<td>n/a</td>
<td>n/a</td>
<td>?</td>
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<tr>
<td>Ops Systems Sustaining Eng./yr.</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>?</td>
</tr>
<tr>
<td>Ops costs/yr.</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>?</td>
</tr>
<tr>
<td># of years</td>
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<td>90 days</td>
<td>1-2 years</td>
<td>50 +</td>
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<tr>
<td>Total program cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Exploration**
  - High
  - ?
  - ?
  - ?
  - 50 +
The New Explorers and New Operations

**Concept of Operations:** Robotic assistants explore while people monitor and control from safe havens.

**Machine systems**
- physical strength, power, reach
- computational power, analysis
- communications
- continuous performance
- automation as a team player

**People**
- Active scientific discovery
- Hypothesis testing
- Creative problem-solving
- Strategic decision-making / Replanning
- First-hand experience and Communications to earth
Lunar Mission Operations
Functional Trade Space

Lunar Network & Vicinity Operations
Lunar Mission Scenarios
Global Surface Access, 7 Day Duration
South Pole Region, 30-90 Day Duration

Earth-based vs. On-board *
System Monitoring & Control

Science & Payload Ops
Earth-based vs. On-board *

Element Trades
(Decision and Analysis Categories)
Communications
Life Support
Crew Activity Planning
Robotic Activity Planning
Vehicle Monitoring & Control
Surface Asset Monitoring & Control

Earth-Moon Transit Operations

System Monitoring & Control
Earth-based vs. On-board *

Trajectory Management & Ascent / Descent
Earth-based vs. On-board *

Earth Network & Vicinity Operations

System Monitoring & Control
Earth-based vs. On-board *

Ascent / Descent & Landing
Earth-based vs. On-board *

* Combined Options Allowed
## 9.1.5 Mobility/Hybrid Human/Robotic Control Roadmap

<table>
<thead>
<tr>
<th>Technology</th>
<th>Years to Develop to TRL 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid human/autonomous mobility: proximity/long range traverse*</td>
<td>4-5</td>
</tr>
<tr>
<td>Fused control sensor suite</td>
<td>4</td>
</tr>
<tr>
<td>S/W control architecture</td>
<td>5</td>
</tr>
<tr>
<td>Autonomous fault ID/management and early propagation detection</td>
<td>2-3</td>
</tr>
<tr>
<td>Autonomous resource management</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technology</th>
<th>SOA</th>
<th>TR4</th>
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</thead>
<tbody>
<tr>
<td>Hybrid human/autonomous mobility: proximity/long range traverse*</td>
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<tr>
<td>Fused control sensor suite</td>
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<tr>
<td>S/W control architecture</td>
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<td></td>
<td></td>
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<tr>
<td>Autonomous resource management</td>
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</tr>
</tbody>
</table>

Note: *While it is understood that both the Apollo rover (human controlled) and MER (semi-autonomous) are TRL8, the redesign of both systems to accommodate seamless hybrid control has not been achieved and will require significant design and integrated testing—this is somewhat reflected in the other critical technology development roadmaps.
Some Lunar Base Need Candidates

Power generation, transmission, and storage

Fuel and water generation, transmission, and storage

Environmental control

Dust control

Communications

Building materials production

Dirt movement

Construction - buildings, roads, landing port, science/industrial facilities

Navigation

Maintenance

Surveying

Human and materials transportation
Redundancy – one more massive and expensive large capacity robot to do the job or several smaller less expensive and robots who together could do the job in the same time or the same job in a longer time in the presence of failures.

Interoperability – using components of robotics in multiple machines, e.g., power supplies, computers, end effectors, …

COTS based – web-based packet communications, standard interfaces (e.g., USB, Firewire, data and mechanical connection), commonly-available components and subunits.
Generalized workers – robots that can perform a variety of tasks

Standardization – develop and use new international robotic standards

Alterability – be re-programmable and physically alterable for new tasks or to recover from unplanned events or failures

Controllability - autonomous operations with override capability and provisions for tele-robotic control
Potential Lunar Robot Examples

- Scout
- Dirt mover
- For Hire
- Transport
- Trencher
- Burrower
- Lunar dirt settler
- Dirt solidifier
- Crew assistant
- Plumber/Wirer
- Crane

For Hire
Challenges for Exploration Robotics

• Qualify robotic designs for outer space environments

• Minimize time latency effects for earth-based ground control methods

• Conduct surface robot operations near lunar noon

• Conduct surface robot operations during Martian blowing dust times

• Make further advances in perception and “cognition”
  (see examples next page)

• Secure and redundant command paths
• Intake of visual, auditory, and tactile sensory inputs → rapid recognition of objects

• Physical path planning in presence of many multiple types of constraints

• Logical layering of hierarchical control mechanisms
dumb behaviors building up to complex behaviors
[e.g., single joint movement ... basic skill (grasp) ... tasks with multiple skills (go fetch panel)]

• Transformation of high level commands to a sequence of skills including constraints checking and intelligent reaction to these constraints

• Inter –robot information and skill transfer

• Operating in the environment of non-cooperative agents (e.g., robots avoiding interference with the actions of other robots and with carbon-based units)

• Self-starting actions based on perceived needs (within constraints)