Space Robotics

Robotics Technology and Programs
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Preview
Robotics Technology Assessment
• Current areas of research
• State of technology maturity

Programmatic Needs
• NRC Solar System Exploration Survey
• NASA Vision for Space Exploration

Space Robotics Researcher

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• Scientist in the Robotics Institute
• Post-doc at NASA Ames

Research Area
Robotic Exploration

Objective
To develop the methods and practice needed to engage robots in scientific discovery and meaningful work

Space Robotics at Carnegie Mellon

Creating new ideas and approaches
Space robot concepts and prototypes
• Amber, 1989
• SM², 1991
• Dante I, 1992
• Tesselator, 1993
• Dante II, 1994
• Ratler, 1995
• Nomad, 1997
• Bullwinkle, 1998
• Skyworker, 1999
• Hyperion, 2001
• Zoë, 2004

Experimental analysis in relevant environments
Field experiments:
• Antarctica, 1992
• Alaska, 1994
• Chile, 1997
• Antarctica, 1998, 1999, 2000
• Canada, 2001
• Chile, 2003, 2004
### Space Robotics at Carnegie Mellon

**Technology infusion and mission development**
- Rover Software
  - TCA/TDL
  - IPC
  - Morphin (Gestalt)
  - D*
  - TEMPEST/ISE
  - Hyperion Navigator
- Mission Proposals
  - Icebreaker
  - Victoria
  - Long Day’s Drive
  - HOMER

### Space Robotics at Carnegie Mellon

**Training technologists and leaders**
- Carnegie Mellon people to and from:
  - NASA Ames
  - NASA Johnson
  - NASA Kennedy
  - NASA Goddard
  - Jet Propulsion Laboratory
  - Probably all the NASA centers

### What is a Space Robot?

**Attributes?**
- Abilities?
- Challenges?

### Space Robotics Missions

- Deep Space
- Near Space
- Ground Service
- Assembly & Maintenance
  - Exploration
  - Flyby
  - Orbiter
  - Lander
  - Rover

### Space Robotics Technology Assessment

**Assess current and future state-of-art of space robotics:**
- Mission feasibility
- Technology gaps

Robots have been used since the beginning of space exploration (Lunakhod, 1970)

**What limits current robots?**
**What does the future hold?**
Near Space Capabilities

Assembly
- Transporting and mating of components; making connections; assembling small structures
- Planning and execution; assembling small structures
- Making connections; assembly sequence planning and execution; assembling small structures

Inspection
- Visual inspection of exterior spacecraft surfaces; path planning and coverage planning; automated anomaly detection

Maintenance
- Change-out of components; accessing obstructed components; robotic refueling

Human EVA Interaction
- Monitoring and documenting EVA tasks; prepping a worksite; interacting with astronauts; human-robot teaming

Near-Space Assembly

Currently Possible:
- Autonomous assembly of carefully designed mechanism in a static, known environment
- Autonomous mating of robot-friendly connectors

Needs Work:
- Recovering from errors/perturbations
- Design and control of high DOF robot systems
- Manipulation of fragile components

Significant Challenge:
- Autonomous assembly planning including responding to unforeseen situations

Near-Space Robotic Assembly Evaluation

Teleoperated robots that move large components and mate parts
- Closely supervised, semi-autonomous robots that move large components and mate parts
- Teleoperated robots that can mate parts and make fine connections between parts
- Autonomous robots that move large components and mate parts with minimal human intervention
- Autonomous robots that mate parts and make fine connections between parts with minimal human intervention
- Autonomous robots that perform complete assembly of complicated structures (e.g., large telescope) from start to finish with substantial support from ground-based or Near-Space humans
- Autonomous robots that perform complete assembly of complicated structures (e.g., large telescope) from start to finish with minimal human intervention

Near-Space Assembly Examples

Ranger
- Tele-operated crane
- Requires special connectors
- Limited mobility

Skyworker
- Transport of objects
- Low-energy climb on structure

Space Station RMS
- Tele-operated crane
- Requires special connectors
- Limited mobility

Other Systems
- Robonaut
- Langley Assembly Robot
- ETS-V5
- ROTEX
- ERA
- JEM Fine Arm
- SPDM
Near-Space Robotic Inspection

Currently Possible:
• Mobility and coverage of the exterior of complex structures
• Autonomous refueling/recharging of inspection robot

Needs Work:
• Accessing interior spaces (perhaps using “snake” or other high DOF robots)

Significant Challenge
• Autonomous anomaly detection

Near-Space Inspection Evaluation

Robotic visual inspection of some exterior surfaces with no interpretation of sensory data; teleoperated

Robotic visual inspection of some exterior surfaces; sensory data filtered before being stored or sent; supervised autonomous operation

Robotic visual inspection of most exterior surfaces; autonomous interpretation of most data; autonomous refueling and recharging

Near-Space Inspection Examples

AERCam Sprint
Teleoperated free-flying camera
Flown on space shuttle

Inspector
Failed in space experiment
Designed for autonomous and teleoperated operation

AERCam IGD and AVIS
Autonomous inspection
Path planning and coverage

Other Systems
• Charlotte
• PSA (IVA robot)

AERCam (JSC)

AERCam consists of two parts:
• Hardware platform for external inspection
  Thrusters, Cameras, GPS, Wireless
  Compact size (8 in diameter)
• Software for sensing, reasoning and interface capabilities that automate both routine and anomaly-driven external inspection:
  Autonomous, safe navigation
  Autonomous anomaly detection
  Improved crew interfaces and situational awareness

Near-Space Robotic Maintenance

Currently Possible:
• Autonomous change-out of components that are designed for replacement
• Accessing components behind covers under teleoperation

Needs Work:
• Autonomous change-out of components not designed to be replaced
• Accessing components behind covers, blankets, etc. under supervised autonomy
• Interaction with badly damaged components

Significant Challenge
• Advanced troubleshooting
**Near-Space Maintenance Evaluation**

- Robotic change-out of pre-designed components (e.g., ORUs) under teleoperated control
- Robotic refueling of spacecraft/satellites under teleoperated control
- Robotic manipulation of pre-designed ORUs under teleoperated control

**Near-Space Maintenance Examples**

- **Robonaut**
  - High DOF gripper
  - Compliant gripper
  - Telepresence interface

- **DEXTER**
  - Attaches to end of RMS
  - Multi-arm dexterous manipulation system

- **ROTEX**
  - Flown on space shuttle
  - Performed simple assembly and change-out

- **Other Systems**
  - Skyworker
  - ETS-VII
  - Ranger
  - Progress re-supply vessels

**Ranger (University of Maryland)**

- **Program Objectives**
  - Robotic System Performance: Characterization of the performance of the various components of the robotic system, along with demonstration of representative EVA and EVR servicing tasks.
  - Human Factors Effects: Effects of local and remote teleoperation of the robotic system, and potential mitigating techniques that may be applied to the user interface.
  - Correlation of Flight Data to Ground Simulations: Validate the database from computer graphic and neutral buoyancy simulations developed in support of the flight mission.

**Ranger Robot Capabilities**

- **Four Robotic Manipulators**
  - Two, 8 DOF dexterous arms with:
    - Four Robotic Manipulators
    - Wrist video camera
    - Minimum of 30 lb capability at the tool tip throughout the work envelope
    - 63" maximum reach
    - Two tool drives for End Effector control
  - One, 7 DOF video arm with stereo video pair
    - Independence controlled LED lighting
  - One, 6 DOF Positioning Leg
    - Positions Ranger at each work site and puts Ranger into RLM
    - 63" maximum reach
  - ROTEX
  - Flown on space shuttle
  - Performed simple assembly and change-out

**Near-Space EVA Assistance**

- Currently Possible:
  - Tracking of EVA astronauts
  - Physical interaction with astronaut by holding/handling tools
  - Recognition of gestures and natural language commands
  - Site preparation given specific requirements

- Needs Work:
  - Site preparation based on task
  - Free-flowing dialog between robot and human
  - Recognition of human emotional and physical condition

**EVA Assistance Overall Evaluation**

- Robotic refueling of spacecraft/satellites under teleoperated control
- Robotic change-out of arbitrary exposed components under teleoperated control
- Robotic access to and change-out of arbitrary, obstructed components under teleoperated control
- Robotic troubleshooting of anomalies and arbitrary repair under teleoperated control

- Robotic change-out of pre-designed components (e.g., ORUs) under teleoperated control
- Robotic refueling of spacecraft/satellites under teleoperated control
- Robotic change-out of arbitrary exposed components under teleoperated control
- Robotic access to and change-out of arbitrary, obstructed components under teleoperated control
- Robotic troubleshooting of anomalies and arbitrary repair under teleoperated control
**Near-Space Assistance Examples**

**Robonaut**
- High DOF grippers
- Compliant grip
- Telepresence interface
- Teleoperated crane
- Can move EVA astronauts around

**RMS**

**Ranger**
- Teleoperated
- Tested in Neutral Buoyancy Facility

**Other Systems**
- FTS

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**Surface EVA Assistance**

Currently Possible:
- Following of human (e.g., "pack mule")
- Site reconnaissance and mapping
- Gesture recognition
- Plan recognition

Needs Work:
- Site clean-up (e.g., picking up tools, setting up experiments)
- Dialog with human crew
- Recognition of human mental and physical state

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**EVA Assistance Evaluation**

Robot tracks an EVA crew member while carrying tools and a camera

Robots do site survey and preparation as well as post-EVA documentation

Robots carry tools, which they hand to the EVA crew member. Robots can also collect designated samples

Robots physically interact with humans via high-level voice commands and gestures

Synergistic relationship between human and machine with direct, physical connections and prostheses, i.e., "super" humans augmented with machines

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**ERA Robot Capabilities**

**Autonomous traversal of rugged terrain via**
- GPS
- Stereo vision for terrain mapping
- Custom designed base

**Tracking of suited crew member**
- Stereo vision with BiCLOPS head
- Voice recognition
- IBM ViaVoice

**Manipulation**
- 7DOF manipulator
- Barrett hand
- Dedicated trinocular vision system

**Wireless connection to/from suit**

**Distributed control infrastructure**

**Remote workstation**

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**Planetary Surface Mobility**

Currently Possible:
- Localization and local mapping
- 100’s of meters between command cycles
- Coverage patterns
- Visual servoing
- Obstacle avoidance

Needs Work:
- Most terrain types with specialized machines
- Globally consistent mapping
- Robust navigation

Significant Challenge:
- Single vehicle that can access all terrain types, cover long distances, survive 1000 days AND carry a payload....
- Robust self-recoverable mechanisms

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**Robonaut (JSC)**

Robonaut is a humanoid robot being designed at NASA Johnson Space Center in cooperation with DARPA.

It consists of two arms, two hands, a head and a waist.

It is currently teleoperated with a small amount of autonomy. Future advances in autonomy are planned.
**Extreme Terrain Access, Dante (CMU)**

Can access most terrain types with specialized systems (robots and supporting infrastructure)
- Dante I and II volcano explorers
- Tethered descent

**Long Distance Traverse, Nomad and Zoë (CMU)**

Can cover large distances with appropriately sized and specialized rovers
- Nomad
  - Teleoperated 230km
- Zoë
  - Autonomous 10km/day

Again, the challenge is building general systems that can access many kinds of terrain, travel long distances, be sufficiently light and carry a payload.

**Surface Traverse Distance**

Traverse distance per command cycle

- 1 m
- 10 m
- 100 m
- 1000+ m

Flight SOA

Fielded SOA

10 year Forecast

**Instrument Deploy & Sample Manip.**

Currently Possible:
- Visual servoing to target
- Contact measurements

Needs Work:
- Robust visual servoing combined with SLAM to visit multiple targets in a single command cycle.
- Precise contact measurements and autonomous sample manipulation

Significant Challenge:
- Drilling to 1000m depth (Mars conditions)

**Approach & Instrument Placement**

Command cycles / operation:
- Remote measurements
- Single surface contact measurements
- Precise surface contact measurements
- Multiple targets in single cycle, highly autonomous

- Multiple
- Multiple
- Single
- Highly autonomous

Flight SOA: Fielded

18 year Forecast

**K9 Rover Target Assessment**

Scientist designated area
- Anywhere on rock
- Segment rock from ground
- Patches consistent with instrument requirements
- Sub-patches in manipulator workspace
- Effect of ground and other rocks
- List of possible instrument poses with allowed error bounds and surface normals

\[ \mathbf{X}_1, \mathbf{S}_1, \mathbf{X}_2, \mathbf{S}_2 \]
K9 Rover Bayesian 3D Rock / Ground Segmentation

Statistical mixture model of 3D dot clouds
• Rock point distribution (spheres)
• Ground point distribution (plane)
Parameter estimation with hidden “nuisance” variables
• K-means clustering
• EM algorithm
Future: geometrical and surface property (color, texture) constraints

Rocky 7 (JPL)

Visual Servoing to Target
Better range estimates
Sense of 3D nature of world
Slower than 2D methods

Marsokhod (NASA Ames)

Surface Instrument Deployment

Nomad 2000 (CMU)
Autonomous approach and placement
Simple environment
Limited robustness.

Other Systems
• FIDO (2001) – autonomous target approach using precise visual navigation (JPL)

Seaioner (JPL)

Surface Sample Manipulation

Robonaut (JSC)
Tele-operated humanoid robot
Human tool use
Visual feedback only

Other Systems
• Autonomous excavators (CMU)
• Sub-surface vehicles (tele-operated)

Viking

Whole Sample Manipulation
Imprecise and unpredictable manipulation
Precise and predictable manipulation
Manipulate complex shapes
Operate in complex environment w/ clutter, constraints and occlusions

Command cycles / operation:
Example manipulators:
• Scoop, channel
• Gripper

Highly autonomous
Significant Challenge

Mars Polar Lander (JPL)

Imprecise and unpredictable
Deliberately limited to avoid tipping over lander

Other Systems
• Autonomous excavators (CMU)
• Sub-surface vehicles (tele-operated)
Science Perception, Plan & Execution

Currently Possible:
- Virtual presence for scientific exploration
- Ground tools for scientists to plan days events.
- Generation and robust execution of plans with
  • Contingencies
  • Flexible times
  • Weakly interacting concurrent activities
- Limited, highly specialized, onboard science perception

Needs Work:
- Limited high level science goal commanding for specialized tasks

Significant Challenge:
- Human level cognition and perception of science opportunities.

VIZ (NASA Ames)

- Virtual environment for scientific visualization (used in 1997 Pathfinder mission)
- Ground planning tool for scientists
- Visual information only

Other Systems
- MER 2003 + WITS
- MSF + ROAMS rover simulators

DS1 / Remote Agent (NASA Ames)

Software for the autonomous planning and execution of basic space-craft functions.
- Plans for and executes prioritized list of goals.
- Constraints amongst tasks.
- Flexible time constraints.
- Contingencies.
- Flown on DS-1 space-craft in 1999.

Onboard Science Analysis

Return all data
- Returns selected data
- Select targets
- Characterize site
- Recognize unforeseen scientific opportunities

Significant Challenge

Nomad (CMU, 2000)

- Autonomous onboard meteorite identification
- Selects targets

Nomad Bayes network rock classifier

Network topology reflecting dependencies.
- Identify rock types
- Sensor feature's with minimum cross dependencies.
- Train network by estimating $P(X|\text{Rock Type})$ from example data.
- Compute posterior probability from sensor data features:
**Assessment Conclusions**

System design is an overarching challenge
- Spiral development because requirements are ill-specified
- Evolving from capability to reliability
- Interaction with pesky humans
- Operating on mission-level objectives
  - Getting beyond tactical autonomy
- Continuing technical challenges

**Challenge of Robustness**

Human level adaptability and response to adversity NOT likely in near future.

Achieved through good system engineering:
- Humans in the loop
- Specialized machines for each task
- Sustained testing
- Diversity technology base

Respond gracefully to unexpected situations:
- Unmodeled situations ➔ beyond orthodox FDIR
  - Adaptation

**Human–Robot Interaction Challenges**

Establishing a virtual presence
- Non-visual feedback such as haptic and proprio-receptive.
- Shared control (low-level control automated)

Adjustable autonomy
- Teleoperation ➔ high-level goal input
- Human-robot teaming
- Human operator to robot ratio
- Interface to non-humanoid robots

**Human Control is Not Safe!**

This situation occurred when humans, overriding the autonomous navigation system, went into a very rocky area.

“Blind” moves and turns were used, compounded by noise on rate gyro.

*[Brian Wilcox, JPL]*

**Mission Level Objectives**

Problem
- Scientific perception and discovery
  - “go there and look for anorthosite”
- Construction
  - “Assemble that strut”

Challenges
- Understanding operator intentions (e.g., what strut)
- Planning in open world and using common sense reasoning
- Complex plan execution in uncertain environment

**Technology Challenges**

Perception and computer vision
Robot health monitoring
Planning, replanning and adaptation
Non-visual feedback to human operator (e.g., haptic, kinematic)
High DOF systems
- Actuation
- Sensing
- Control
- Replication of human dexterity
**Need for Sustained R&D**

Handful of robots flown

Significant gap between flight and terrestrial systems
- Sojourner has more autonomy than was used.

Massive in place infrastructure for human space flight

**Space Exploration Priorities**

Review of the Solar System Exploration Survey by NRC Space Studies Board

**Motivational Questions & Scientific Goals**

Are we alone?
Determine how life developed in the solar system, where it may have existed, whether extant life forms exist...

Where did we come from?
Learn how the Sun’s retinue of planets originated and evolved.
Discover how the basic laws of physics and chemistry, acting over aeons, lead to diverse phenomena...

What is our destiny?
Explore the terrestrial space environment to discover what potential hazards exist.
Understand how physical and chemical processes determine the main characteristics of the planets...

**Scientific Themes for 2003 – 2013**

First billion years of solar system history

Volatile and organics: The stuff of life

Origin and evolution of habitable worlds

Processes: How planetary systems work

**12 Key Scientific Questions → Missions**

First billion years of solar system history
1. What processes marked the initial stages of planet formation?
   - Comet surface sample return (CSSR)
   - Kuiper belt/Pluto (KBP)
   - South pole Aitken basin sample return (SPA-SR)
2. Over what period did the gas giants form, and how did the birth of the ice giants (Uranus, Neptune) differ from that of Jupiter and its gas-giant sibling, Saturn?
   - Jupiter polar orbiter with probes (JPOP)
3. How did the impactor flux decay during the solar system’s youth, and in what ways(s) did this decline influence the timing of life’s emergence on Earth?
   - Kuiper belt/Pluto (KBP)
   - South pole Aitken Basin sample return (SPA-SR)
4. What is the history of volatile compounds, especially water, across our solar system?
   - Comet Surface Sample Return (CSSR)
   - Jupiter Polar Orbiter with Probes (JPOP)
5. What is the nature of organic material in our solar system and how has this matter evolved?
   - Comet Surface Sample Return (CSSR)
   - Cassini Extended mission (CASx)
6. What global mechanisms affect the evolution of volatiles on planetary bodies?
   - Venus In-situ Explorer (VISE)
   - Mars Upper Atmosphere Explorer (MAO)
12 Key Scientific Questions → Missions

Origin and evolution of habitable worlds
7. What planetary processes are responsible for generating and sustaining habitable worlds, and where are the habitable zones in our Solar System?
   - Europa Geophysical Explorer (EGE)
   - Mars Smart Lander (MSL) • Mars Sample Return (MSR)
8. Does (or did) life exist beyond the Earth?
   - Mars Sample Return (MSR)
9. Why have the terrestrial planets differed so dramatically in their evolutions?
   - Venus In-situ Explorer (VISE) • Mars Smart Lander (MSL)
   - Mars Long-lived Lander Network (MLN) • Mars Sample Return (MSR)
10. What hazards do solar system objects present to Earth’s biosphere?
    - Large-aperture Synoptic Survey Telescope (LSST)

12 Key Scientific Questions → Missions

Processes: How planetary systems work
11. How do the processes that shape the contemporary character of planetary bodies operate and interact?
    - Kuiper Belt / Pluto (KBP)
    - South Pole Aitken Sample Return (SPA-SR)
    - Cassini Extended mission (CASx)
    - Jupiter Polar Orbiter with Probes (JPOP)
    - Venus In-situ Explorer (VISE)
    - Comet Surface Sample Return (CSSR)
    - Europa Geophysical Explorer (EGE)
    - Mars Smart Lander (MSL)
    - Mars Upper Atmosphere Orbiter (MAO)
    - Mars Long-lived Lander Network (MLN)
    - Mars Sample Return (MSR)
12. What does our solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa?
    - Kuiper Belt / Pluto
    - Jupiter Polar Orbiter with Probes (JPOP)

Kuiper Belt / Pluto (KBP)

GOALS:
- Investigate the diversity of the physical and compositional properties of Kuiper belt objects
- Perform a detailed reconnaissance of the properties of the Pluto-Charon system
- Assess the impact history of large (Pluto) and small KBOs

Pluto/Kuiper Express (August 2000 Design)

Objective
Conduct the first reconnaissance of the Pluto/Charon system, and attempt to encounter one or more Kuiper objects.

Mission scenario
- Launch in 2004 or 2006 on Delta-4, 11-13 year JGA flight to Pluto
- Small RTG-powered spacecraft (Cassini-space RTG)
- Remote sensing and radio science instrumentation
- Kuiper object flybys as extended mission objective

Mission Options
- Use of solar electric propulsion instead of ballistic JGA trajectory
  - Enables roughly equivalent flight times with launch any year (current task)
  - Improved SEP: flight times <10 years
  - Allows use of smaller launch vehicle
  - Requires Earth flyby
- Use of solar gravity assist trajectories
  - Allows later launch (2007-8)
  - Requires longer flight time or very low perihelion
Missions: Key Scientific Questions

• South Pole Aitken Basin Sample Return (SPA-SR)

A mission to return samples from the solar system’s deepest crater, which pierces the lunar mantle.

• What processes marked the initial stages of planet formation?
• How did the impactor flux decay during the solar system’s youth, and in what ways(s) did this decline influence the timing of life’s emergence on Earth?
• How do the processes that shape the contemporary character of planetary bodies operate and interact?

South Pole Aitken Basin Sample Return

GOALS:

• Obtain samples to constrain the early impact history of the inner solar system
• Assess the nature of the moon’s mantle and the style of the differentiation process
• Develop robotic sample acquisition, handling, and return technologies

Lunar Giant Basin Sample Return

Objective

• Collect and return samples of lunar mantle material from the floor of the South Pole - Aitken basin

Mission scenario (planning baseline)

• Orbiter/lander/rover launched on single Atlas III
• Direct descent trajectory, orbiter diverts to L2 Lagrange point for data relay
• 14 days lunar surface operations
• Subsurface sampling to 2 meters
• Sample collection via tele-operated rover
• Lunar ascent vehicle (LAV) launches 4.6 kg of samples into high Earth orbit
• Orbiter rendezvous with sample return vehicle, sample is transferred to entry vehicle for sample return

Mission Options

• Launch sample directly to Earth - no rendezvous in Earth orbit
• Avoid rendezvous issues and sample transfer, but requires larger launch vehicle
• Rendezvous in lunar orbit
  - Mass penalty due to lunar orbit insertion and escape
• Earth return using auto-entry ballistic
• Link to Earth using Ka-band

Lunar Giant Basin Sample Return

Major or Unique Developments Required

• Soft lunar landing requires development of a thrustersable, high-payload main engine
• Sample collection and handling
  - 2-m deep drill and sample retrieval system on lander
  - Sample cache on rover is brought into sample container on lander
  - Tele-operated sample selection
  - Rover carries monochromatic imaging, visible and near infrared point spectrometer and X-ray fluorescence for sample selection
  - Sampling decisions must be made on Earth in real time
• Ascent from lunar surface
  - Single-stage, solid rocket motor, open-up from lunar lander
• Rendezvous and sample transfer in Earth orbit

• Heritage and Commonality
  - Rover design heritage from Mars missions
  - Mars sample return design heritage for rendezvous and sample capture
  - Sample curation and analysis facilities exist
  - Descent engine could be used at other airless bodies (if low mass)
Lunar Giant Basin Sample Return

Comments and Issues

• Rendezvous in Earth orbit vs. direct return or lunar orb is a key mass/size/risk trade
• Real-time commanding of orbital and surface elements during critical operations
• Surface mission duration limited by power
• LAV orbit injection accuracy is a concern. Additional propellant needed on the orbiter/rendezvous vehicle to accommodate injection errors.
• Mission class: Moderate
• Technology risk: Low to Moderate
• Multimission technology: ~$12M

Jupiter Polar Orbiter with Probes (JPOP)

GOALS:

• Determine if Jupiter has a central core to constrain ideas of its formation
• Determine the planetary water abundance
• Determine if the winds persist into Jupiter’s interior or are confined to the weather layer
• Assess the structure of Jupiter’s magnetic field to learn how the internal dynamo works
• Measure the polar magnetosphere to understand its rotation and relation to the aurora

Missions: Key Scientific Questions

• Jupiter Polar Orbiter with Probes (JPOP)

A close-orbiting polar spacecraft equipped with various instruments and a relay for three probes that make measurements below the 100-bar level.

• Over what period did the gas giants form, and how did the birth of the ice giants (Uranus, Neptune) differ from that of Jupiter and its gas-giant sibling, Saturn?

• What is the history of volatile compounds, especially water, across our solar system?

• How do the processes that shape the contemporary character of planetary bodies operate and interact?

• What does our solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa?

Jupiter Deep Multiprobes

Objective

Study Jupiter’s deep atmospheric composition and dynamics at multiple latitudes.

Mission scenario (planning baseline)

• Three battery-powered probes (80 kg each) carried on single spacecraft
• Probes are released approx. 4 mos prior to Jupiter flyby; trajectories allow entry at different latitudes and different times
• Probes operate down to 100 bars
• Relay spacecraft records data from all three probes and relays to Earth

Mission Options

• Minimum probe depth drives probe mass and power, and required relay arc
  - Shallower probes simplify mission and system design and reduce cost
  - May accept shallower depth from probe #1 (North) to increase link margin from probes #2 and #3
  - Use of RTG rather than solar power (carrier) may reduce risk
• Optimization of perijove link data rate, frequency, and link duration affects total data return
  - Baseline Delta 4 LV, 6 yr total mission duration; 2 yr reduction possible at cost of ~$75M

Major or Unique Developments Required

• Low-mass thermal protection system (55,000K max)
• Materials and designs to be identified
• Some heritage from Galileo Probe
• Test facilities must be reactivated and maintained (arc jet)
• Low-mass pressure vessel (100 bars)
• Communication with reasonable data rate at 100 bar depth through Jovian atmosphere
• Low-mass primary batteries
• Low-mass power UHF communications
• Miniaturized GCMS and other instruments
• Prototype exists - development cost ~$8M

Heritage and Commonality

• Significant Galileo probe heritage
• Improved thermal protection and test facilities
• Benefit most sample return missions, esp. CNSR
• Miniaturized instruments widely applicable, esp. GCMS
• Containerized bus can be very similar to INSIDE Jupiter Discovery proposal
Missions: Key Scientific Questions

- Venus In-situ Explorer (VISE)

A core sample of Venus will be lifted into the atmosphere for compositional analysis; simultaneous atmospheric measurements.

- What global mechanisms affect the evolution of volatiles on planetary bodies?
- Why have the terrestrial planets differed so dramatically in their evolutions?
- How do the processes that shape the contemporary character of planetary bodies operate and interact?

Venus In-situ Explorer (VISE)

GOALS:
- Determine the compositional and isotopic properties of the surface and atmosphere
- Investigate the processes involved in surface-atmosphere interactions
- Elucidate the history and stability of Venus’s atmospheric greenhouse

Major or Unique Developments Required
- Miniaturized in situ instruments
  - Miniaturized high-gain (CHMG) (prototype exists)
  - Miniaturized age dating system (life-time)
  - Other instruments: VIK, HIRIS are heritage
- Irradiation system for survival on Venus surface
  - Pressure vessel with CUO outer layer and In steel inner layer
- Super pressures balloon balloon material/cryostat
  - Thermo-coated performance measurement (0K at tested
  - Pressure balloon inflation for safe ascent
- Sample acquisition and handling
  - Ultrasonic drill prototype exists
  - Sample-transfer at Venus surface pressure
- Heritage and Commonality
  - Mars Pathfinder crater system and aeroshell design
  - Viking XRF, Huygens descent imager/radiometer
  - Phoenix/Genesis/VEGA/Venera thermal and balloons
  - Ultrasonic drill common with MSR, CNSR
  - Instruments in situ instruments widely applicable

Venus In-Situ Exploration

Objective
- Conduct Venus surface/atmosphere measurements
- Validate techniques for future Venus surface sample return

Mission Options
- Lander delivery from Venus orbit
  - Improves site selection and delivery accuracy but adds cost
  - Insertion into orbit via aerocapture would validate additional technology for VSSR but not required for precursor science mission
- Extend surface survival time to cover primary data relay instead of raising to altitude
  - Reduces risk that balloon failure could compromise primary science goals
  - Significant mass and cost impact to Venus In-Situ Exploration (VISE)
  - Balloon inflation and ascent is a major element of future VSSR mission

Jupiter Deep Multiprobe

Comments and Issues
- Potential for continuing science following probe data relay
  - Helioseismic (sun) science
  - Coral auroral encounter?
  - Possible capture into loose Jupiter orbit?
- Number of probes could be increased to 4; trade with data return from individual probes
- Similar mission design is possible for Saturn multi-probes
- Mission Class: Moderate
- Technology risk: Low to Moderate

Cost (RY$, FY12 launch)
- Development: $180 - 225M
- Mission Operations: $25 - 30M
- Launch Vehicle: $95M
- Multimission technology: ~$18M

Venus In-Situ Exploration

Comments and Issues
- Mission must achieve the proper balance of science and technology objectives

Key VISE Technologies

- Included
  - Aerocapture
  - Sample transfer
  - Balloon ascent/mobility

- Not Included
  - Aerocapture/habitat
  - Surface survival - passive
  - Drill sample acquisition

Cost (RY$, FY12 launch)
- Development/launch: $160 - 225M
- Mission operations: $20 - 30M
- Multimission technology: ~$25M

Venus In-Situ Exploration

Objective
- Conduct Venus surface/atmosphere measurements
- Validate techniques for future Venus surface sample return

Mission Options
- Lander delivery from Venus orbit
  - Improves site selection and delivery accuracy but adds cost
  - Insertion into orbit via aerocapture would validate additional technology for VSSR but not required for precursor science mission
- Extend surface survival time to cover primary data relay instead of raising to altitude
  - Reduces risk that balloon failure could compromise primary science goals
  - Significant mass and cost impact to VISE
  - Balloon inflation and ascent is a major element of future VSSR mission

Venus In-Situ Exploration

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- Conduct Venus surface/atmosphere measurements
- Validate techniques for future Venus surface sample return

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**Missions: Key Scientific Questions**

**Comet Surface Sample Return (CSSR)**

Several pieces of a comet’s surface will be returned to Earth for elemental, isotopic, molecular, mineralogical, and structural analysis.

- What processes marked the initial stages of planet formation?
- What is the history of volatile compounds, especially water, across our solar system?
- What is the nature of organic material in our solar system and how has this matter evolved?
- How do the processes that shape the contemporary character of planetary bodies operate and interact?

**Comet Nucleus Sample Return**

Objective

Return pristine samples of volatile materials from a comet nucleus for analysis on Earth

Mission scenario (planning baseline)

- Rendezvous with and orbit an active short-period comet using SEP
- 30-day mapping for site selections; separate lander descends to surface
- Anchor and drill samples from >1 meter depth, minimum 2 sites, rendezvous with orbiter
- Samples maintained cryogenic during Earth return (SEP) and direct ballistic entry

Mission Options

- "Full science" with drilling to 1 m at multiple sites, well documented, vs. "grab sample" - Major implications for science return and cost
- Use of SEP for both outbound and return trajectories - SEP provides best mass performance and flight time
- Dust may affect solar array performance, esp. if single s/c option

**Comet Surface Sample Return**

GOALS:

- Return near-surface cometary materials to Earth for detailed compositional, isotopic, and structural analysis
- Assess the detailed organic composition of the cometary nucleus
- Assess the porosity and other physical properties of nuclear material
- Assess the physical relationship among volatiles, ices, organics and refractories and their relationship to porosity
- Assess the isotopic and mineralogic content at both microscopic and macroscopic scales assess the detailed organic composition of the cometary nucleus

**Comet Surface Sample Return (CSSR)**

**Comet Nucleus Sample Return**

**CNSR in the Sequence of Comet Exploration Missions**

- CNSR launch opportunities occur almost every year
- Launch as early as 2007 - 2008 is feasible, depending on science and sampling goals
- Key project decisions should build on results of current/ planned comet missions
- Coordination with MSR sample handling and analysis facilities will reduce costs

**Cost (RY$, FY11 launch)**

Year: 2005 - 2015

CNSR Example: 2011 launch to Comet Brooks 2

**Comments and Issues**

- CNSR fits logically within the progression of comet exploration missions:
  - Basic nature of the nucleus - Giotto, DSI
  - Diversity of comets - CONTOUR
  - Nature of the subsurface - Stardust
  - Internal strength/structure - Deep Impact
  - Active surface processes - Rosetta
  - Volatile inventory - CNSR

- CNSR is one of the few missions to outer solar system destinations that does not require RTGs

- Wide range of science/technology options can be explored; key driver is surface vs. drilled sample and cryogenic preservation

- Ground sample handling costs not estimated; expect significant leverage with MSR

- Multimission technology development costs ~$45M for key technologies

- Mission class: Moderate to large

- Technology risk: Moderate

**Comet Nucleus Sample Return**
**Missions: Key Scientific Questions**

**Europa Geophysical Explorer (EGE)**

An orbiter of Jupiter’s ice-encrusted satellite will seek the nature and depth of its ice shell and ocean.

- What planetary processes are responsible for generating and sustaining habitable worlds, and where are the habitable zones in our Solar System?
- How do the processes that shape the contemporary character of planetary bodies operate and interact?

**GOALS:**

- Assess the effects of tides on the satellite’s ice shell to confirm the presence of a current global subsurface ocean.
- Characterize the properties of the ice shell and describe the three-dimensional distribution of subsurface liquid water.
- Elucidate the formation of surface features and seek sites of current or recent activity.
- Identify and map surface compositional materials with emphasis on compounds of astrobiological interest.
- Prepare for a future lander mission

**Current Missions**

- Galileo
- Cassini

**Planned Missions**

- Europa

**Propulsion Subsystem (CBE)**

- Delta-4H launch in 2008, direct to Jupiter (2.5 yrs)
- Propulsive capture into Jupiter orbit, 1.5 year gravity assist tour to reduce energy
- Propulsive capture into 200 km Europa orbit
- 30-day primary science mission, followed by maneuver to achieve quarantine orbit

**Mission scenario**

- Delta-40 launch in 2008, direct to Jupiter (2.5 yrs)
- Propulsive capture into Jupiter orbit, 1.5 year gravity assist tour to reduce energy
- Propulsive capture into 200 km Europa orbit
- 30-day primary science mission, followed by maneuver to achieve quarantine orbit

**Key Trades**

- Earth gravity assist trajectory reduces launch vehicle size and increases mass margin, but increases flight time to Jupiter by 2 years
- Other Europa exploration modes (e.g. multi-flybys) have been examined as cost-reduction measures but would lead to significant reductions in primary science objectives

**ORBITER**

**Objectives**

- Conduct intensive orbital study of Europa to conclusively determine presence or absence of subsurface ocean, understand formation and evolution of surface, and identify landing sites for possible future missions

**Mission scenario**

- Delta-40 launch in 2008, direct to Jupiter (2.5 yrs)
- Propulsive capture into Jupiter orbit, 1.5 year gravity assist tour to reduce energy
- Propulsive capture into 200 km Europa orbit
- 30-day primary science mission, followed by maneuver to achieve quarantine orbit

**Challenges of Europa Environment**

- The Europa Orbiter must operate with high reliability during the 30 day mission
  - Science objectives
  - Achieves quarantine orbit
- Delta-V requirements are very high
- Impact
  - New electronics technology
  - Development (2X000) to reduce mass and risk
- Total shielding = 39 kg

**Contingency—budgetary**

<table>
<thead>
<tr>
<th>Science</th>
<th>Propulsion</th>
<th>Propellant (fully loaded)</th>
<th>Contingency (dry)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 kg</td>
<td>273 kg</td>
<td>150 kg</td>
<td>39 kg</td>
</tr>
</tbody>
</table>

**MASS BREAKDOWN**

- Propulsion Subsystem: 273 kg
- Propellant (fully loaded): 150 kg
- Contingency (dry): 39 kg
- 170 kg: 101 kg, 50 kg, 20 kg

**Comment and Issues**

- Independent panels have identified a Europa orbiter as the only mission that can reliably achieve the primary science objectives
- Independent cost assessments show very good agreement with project cost estimates
- X2000 avionics technology has been selected for a number of space science missions; significant industry interest
- Primary remaining project risks are launch vehicle certification and cost, radiisotope power source selection, completion of X2000 avionics, and understanding of radiation effects
- Mission class: Large
- Technology risk: Moderate (on tasks to go)

**Cost (as of May 2001)**

- Development: $790M
- Launch vehicle: 170
- Operations: 120
- Subtotal: 1050
- Mission and lander: 50
- Total life cycle: $1080M

*Notes:* Includes X2000 completion costs
*Includes reserves and contingency
*Includes KEI ($145M)
Europa In Situ Exploration

Objective
Following Europa Orbiter, conduct the first surface exploration of Europa in the next science and technology step in a decadal exploration program.

Mission scenario (planning baseline)
- Carrier vehicle enters Europa orbit following a 2-year gravity assist tour of the Jupiter system
- 2-week mapping in Europa orbit for site selection
- Europa Pathfinder deployed for airbag landing
- 3-day surface mission, data relay via orbiter
- ~25Gbits data return

Mission Options
- D52-style penetrators rather than airbag lander
  - Limits instrumentation but may enable multiple landers
  - Limited technology validation for future missions
- “Powerstick” radioisotope system coupled with secondary battery can increase lifetime at added cost

Elements of a Europa Exploration Program
- Voyager and Galileo
- Europa Orbiter
- Surface experiments: Science and technology pathfinders
- Soft landers, mobile science stations
- Subsurface exploration: ice and/or water mobile platform (“cryobot”)
- Sample return from the surface or subsurface

Major or Unique Developments Required
- Low-mass chemical propulsion for descent
- Enables significant payload increase vs. baseline
- Low-mass, survivable avionics (extension of Europa Orbiter)
- Minimized in situ instruments

Heritage and Commonality
- Off-the-shelf solid rockets for de-orbit and descent
- Mars Pathfinder airbag technology (thermal validation required)
- Carrier has very significant commonality with Europa Orbiter

Missions: Key Scientific Questions

Mars Upper Atmosphere Orbiter (MAO)

GOALS:
- Determine the dynamics of the middle and upper atmosphere
- Determine the rate of atmospheric escape
- Measure the current neutral gas and ion abundances and escape fluxes

Cost (very rough)
- Carrier spacecraft: approximately $500-600M
- Pathfinder lander: 125
- Launch vehicle: 125
- Operations/data analysis: 100
- Total: $825-925M
- Multimission technology: $20M

Comments and Issues
- Europa Pathfinder attempts to identify the minimum surface mission that can make a meaningful contribution to a long-term Europa exploration program
- Carrier accommodation issues have not been addressed in detail
- Payload mass is severely limited by current chemical propulsion technology
- Planetary protection constraints are not well understood and may fundamentally limit future Europa surface exploration
- Mission class: Large (carrier + lander)
- Technology risk: Moderate to High

Mars Smart Lander (MSL)

A lander to carry out sophisticated surface observations and to validate sample return technologies.

- What planetary processes are responsible for generating and sustaining habitable worlds, and where are the habitable zones in our Solar System?
- Why have the terrestrial planets differed so dramatically in their evolutions?
- How do the processes that shape the contemporary character of planetary bodies operate and interact?

Mars Scientific Questions

- What global mechanisms affect the evolution of volatiles on planetary bodies?
- How do the processes that shape the contemporary character of planetary bodies operate and interact?
Mars Smart Lander (MSL)

GOALS:
• Mineralogy, chemistry, and geology of a water-modified environment
• Establish ground-truth for orbital observations
• Measurement of atmospheric properties
• Test for the presence of organics
• Test and validate technology required for sample return

Missions: Key Scientific Questions

Mars Long-lived Lander Network (MLN)

A globally distributed suite of landers equipped to make comprehensive measurements of the planet’s interior, surface and atmosphere.

• Why have the terrestrial planets differed so dramatically in their evolutions?
• How do the processes that shape the contemporary character of planetary bodies operate and interact?

Mars Sample Return (MSR)

GOALS:
• Return samples to Earth from a site selected on the basis of remotely sensed and in situ data that will address key scientific questions
• Precisely measure the geochemical, mineralogical, and volatile content of samples in Earth laboratories
• Assess the biological potential of Mars
• Provide the ultimate ground truth for orbital and in situ data to guide future exploration

Missions: Key Scientific Questions

Cassini Extended Mission (CASx)

Extension of orbiter mission at Saturn

• What is the nature of organic material in our solar system and how has this matter evolved?
• How do the processes that shape the contemporary character of planetary bodies operate and interact?
• What does our solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa?
Cassini Extended Mission (CASx)

GOALS:
- Follow up on significant discoveries during the nominal mission
- Extension of spatial coverage on Titan through changing orbital geometry
- Extension of time coverage of dynamical phenomena at Saturn and Titan

Titan In Situ Exploration

Objective
Conduct in situ exploration of Titan's atmosphere and surface as the next step beyond Cassini/Huygens

Mission scenario (planning baseline)
- Launch to Saturn in 2010 or beyond, SEP or gravity assist trajectory - flight time 6-10 years
- Insert into Saturn orbit, ballistic aerocapture at Titan
- Ballistic entry at Titan, balloon mobility and surface sampling, possible lander package
- Orbital and in-situ observations, 3-year orbital mission, 3-year in-situ mission

Mission Options
- Range of in-situ platforms is possible: Simple lander, mobile lander, simple balloon, balloon (controlled balloon)
  - Mobility for multiple surface site sampling appears to be a key science driver
  - Mass plan for variety of surface conditions
  - Balanced balance of surface and atmospheric observations
  - Orbital science may be eliminated in favor of in-situ science to save cost
  - Orbiter for telecommunication is probably required, but could be under study for direct-to-Earth

Cost (RY$, FY '10 launch)

Development/launch: $950-1125 M
Mission operations: $150-200 M

Titan In Situ Exploration

Asteroid Sample Return

Objective
Return well-documented samples of surface and sub-surface materials from one or more asteroids

Mission scenario (planning baseline)
- Rendezvous with and orbiter a near-Earth asteroid (660 Nereo)
- Map for site selection, simple spacecraft descends, anchors to surface
- Surface and shallow subsurface materials collected from a single site
- Spacecraft departs asteroid, returns to Earth for direct entry
- Total flight time ~3 years, Delta 4240 LV

Mission Options
- Return to Eros may minimize mission cost and risk
- Multiple landing sites may be feasible - enhances science return but increases cost/risk
- Depth of subsurface access required, if any, drives sample system complexity and cost
- Multiple targets could be sampled in a single mission using SEP
- SEP enables access to greater number of targets, including mass-belt asteroids
  - Increases flight time (~7 years for Vesta sample return)
**Asteroid Sample Return**

**Comments and Issues**
- Launch opportunities available virtually every year
- New technologies could enhance science return
  - Surface and subsurface drilling
  - Sample handling technologies
  - Hazard avoidance
- Planetary protection issues affect some classes of asteroids and may increase costs
- Main Belt Asteroid Sample Return would require:
  - Improved SEP (propellant throughput)
  - High-efficiency solar arrays
  - Semi-autonomous navigation and landing
- Mission class: Moderate
- Technology risk: Low

*Cost*

- Development and launch: $300-400M
- Operations: $25-40M

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**Space Exploration Priorities**

- Missions listed in Priority Order
- Missions in bold face were selected by the Steering Group for overall prioritization

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**Space Exploration**

**Vision for Space Exploration**

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**Mars Exploration — This Decade**

- Operational
- 2005
- 2007
- 2009
- ...Next Decade

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**Review**