Autonomous Systems, Robotics and Computing

APIO Workshop Overview

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What is a Capability?

- A Capability defines the *what* is operationally required to perform a function as part of an integrated mission.
- A technology address the how this will be implemented.
- Capability must be situated within a mission context to understand how this will impact the overall mission goals.
- E.g.
  - Localization with a given range of accuracy may be a *what*.
  - GPS, versus SLAM versus visual odometry, etc are *hows*.

Description

The Autonomous Systems, Robotics and Computing roadmap focuses on three broad classes of capabilities that are closely related within many mission concepts.

Autonomous Systems covers capabilities to enable smarter more adaptive systems that can respond to environmental uncertainties both in close cooperation with humans and in remote locations.

Robotics includes the development of integrated robotic systems that require closely coupled, complex interactions with the physical environment often coupling mobility and manipulation mechanisms with embedded autonomy capabilities into an integrated robotic platform.

Computing Systems covers cross-cutting capabilities of computing platforms and technologies for robust software systems to support the other elements of this roadmap as well as other capability roadmaps.

Description

Mission Drivers: Capabilities developed within this roadmap are broadly applicable within the agency. Human exploration will require robotic assistants that interact with humans as well as autonomous reasoning capabilities to support a crew-centered mode of operation. Robotic missions for deep space exploration and earth observation require increased autonomy and sophisticated robotic explorers. Finally, Aeronautics also requires capabilities in this area to support Unmanned Aerial Vehicles.

Scope Note: Within NASA, the phrase "robotic" can be used to describe any unmanned vehicle. Within the broader technology community, however, the definition of a "robot" is often much more narrow and it is used to describe a complex device that can operate independently within a complex environment. For this roadmap we are using the more traditional definition of a "robot". As such, a Mars rover is included under robotics while a spacecraft such as Cassini would not be.

Autonomous Systems, Robotics and Computing is a cross-cutting capability that will provide products to the other Capability Roadmaps as well as directly to the Strategic Roadmaps.

Tentative Sub-Capabilities

Robotics

- Robotic Mobility
- Robotic Manipulation
- Machine Perception
- Navigation and Control

Autonomous Systems

- Planning, Execution and Agent Architectures
- Integrated System Health Management
- Knowledge Representation and Management
- Human-Machine Interaction

Computing Systems

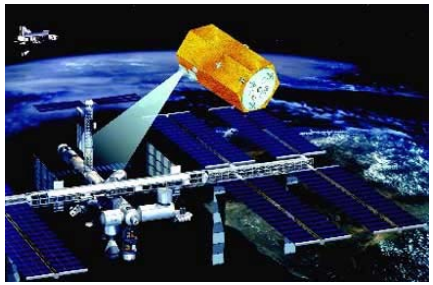
- Robust Software
- On-board Computing Systems
- Reliable Computing Architectures

Robotics Driving Requirements On-Orbit Operations

Assembly

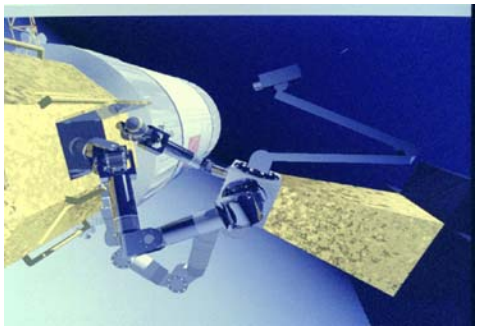
Transporting and mating of components; making connections; assembly sequence planning and execution; assembling small structures

Inspection



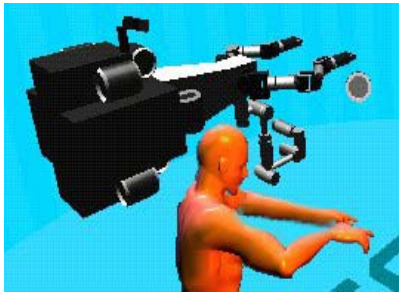
Visual inspection of exterior spacecraft surfaces; path planning and coverage planning; automated anomaly detection

Maintenance



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

Human EVA Interaction

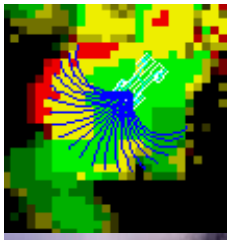


Monitoring and documenting EVA tasks; preparing a worksite; interacting with astronauts; human-robot teaming

Robotics Drivers – Surface Operations

(Reference: NExT Study on Space Robotic Capabilities)

Surface Mobility



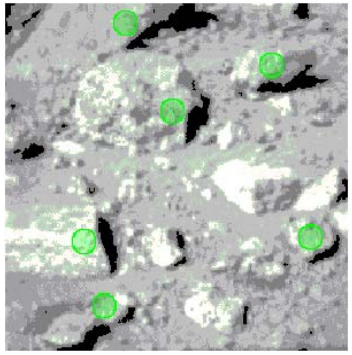
Mobile Autonomy

Terrain assessment, path planning, visual servoing

Mobility Mechanization

Extreme terrain access, energy efficiency

Science Perception, Planning & Execution



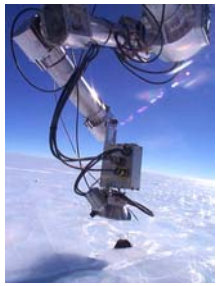
On-board and ground tools; data analysis, target selection, operations planning and execution

Human-Robot EVA Interactions

Tele-operation and human supervision of robotic explorers

Robotic work crews

Instrument Placement and Sample Manipulation

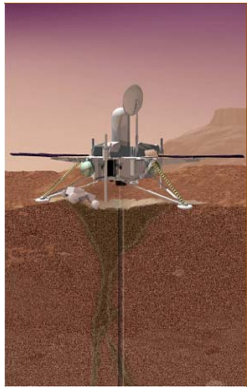


Position sensors, collect and process samples

Motivational Example—Solar System Exploration

Mobility, Safe Landing, Sample Acquisition/Handling, Rendezvous and Sample Capture

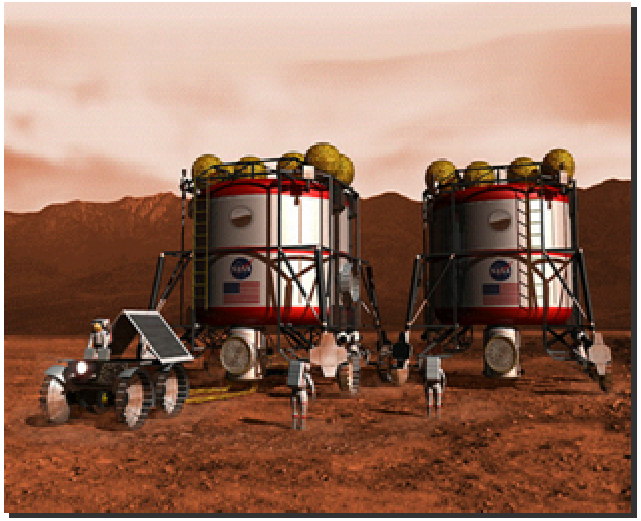
- Rove globally over planetary surfaces and approach local sites (even in extreme terrain) within one pixel of planning image with overall system performance comparable to a field scientist.
- Access subsurface environments including liquid water aquifers or polar caps on Mars, Titan, Jovian moons like Europa, and penetrate through comet nuclei, and deep into lunar and Mercury polar volatiles, etc.
- Fly through atmospheres of Titan, Venus, and Mars to provide superior combinations of coverage and access where possible.
- Land safely within one pixel of a site based on orbital imagery.
- Select, acquire and prepare samples suitable for any in-situ instruments with end-to-end performance comparable to current Earth science processes.
- Acquire, loft, rendezvous/capture, and return to Earth pristine samples within appropriate planetary protection guidelines.
- In an appropriate time frame, conduct cooperative robot-human science activities and habitat support for sustained exploration on lunar and planetary surfaces.



Autonomous Systems Drivers – Lunar and Mars Exploration

- **Crew-Centered Operation**
  - Reduction in size of “standing armies”
  - Reduction in time to respond to off-nominal events
  - Reduction in time spent on maintenance and support tasks
  - Automated assistance for system integration, monitoring and control
  - Support for new in situ tasks such as construction and ISRU

- **Joint human-robotic construction and exploration**
  - Robotic assistants capable of autonomously performing simple tasks
  - Modeling, tasking, and control of integrated teams of humans and robots

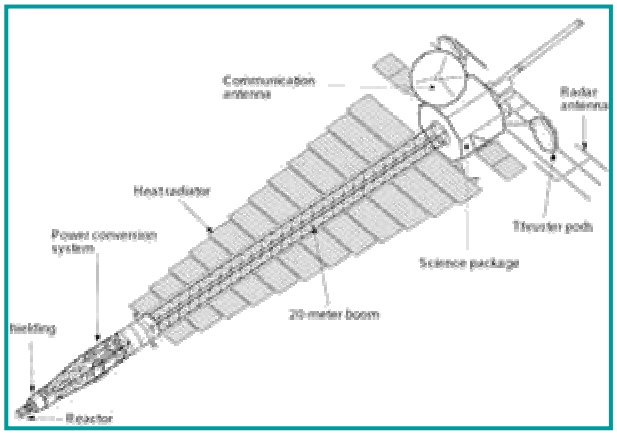


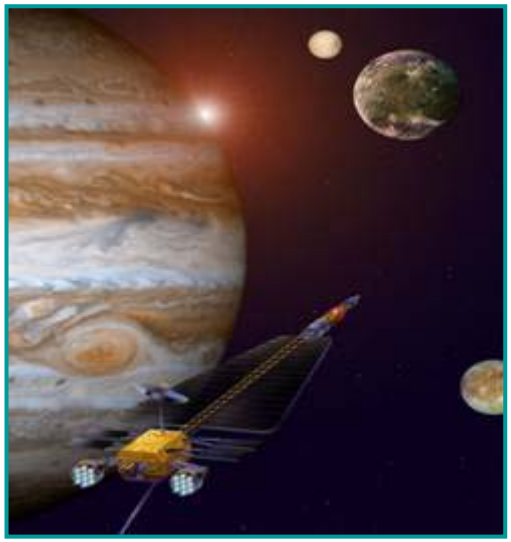
Autonomous Systems Drivers – Lunar and Mars Exploration

- Monitoring and control of environmental systems
  - At the sub-system, system, and habitat level over multiple time scales
  - Must support modular replacement of systems and sub-systems
  - Requiring minimal crew time
- Modeling, planning, and scheduling of crew activities
  - Subject to engineering and human factors constraints
- Interfaces, particularly for EVA, between humans and robotic assistants
- Embedded training and aiding systems
- Autonomous medical care

Autonomous Systems Drivers – Nuclear Technologies

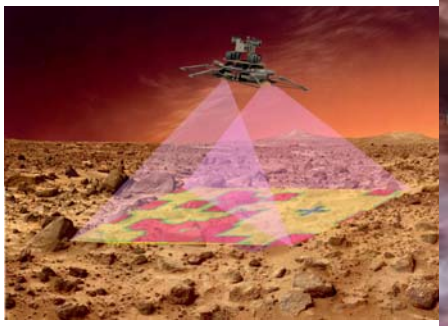
- Rapid situational awareness and anomaly response
  - Includes onboard anomaly response
- IVHM and control for nuclear reactor and ion engine
  - Includes autonomous monitoring and control
- Guidance and control of flexible body in low thrust trajectory
- Planning and sequencing for engineer and science activities
  - Distributed ground operations
  - Onboard adaptation and replanning
  - 24 hour operation, 1500kg of instruments
- ASE for V&V of all software (long life, high robustness requirement)
- Possible Europa lander and/or drill



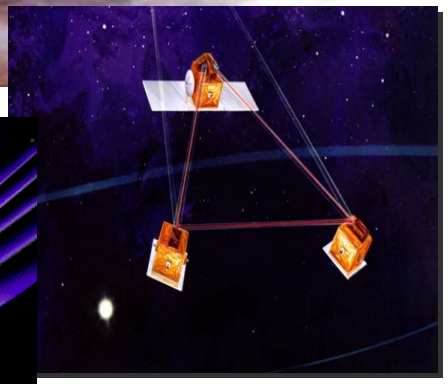


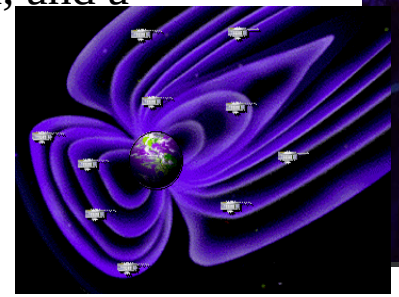
Autonomous Systems Drivers – Robotic Exploration

- Orbital Exploration → Surface Exploration
  - Mars, Titan, Venus, Europa, Moon, small bodies
  - More dynamic, less homogenous environments
  - Significantly more complex behavior
  - Leads to an increased focus on self-reliant systems



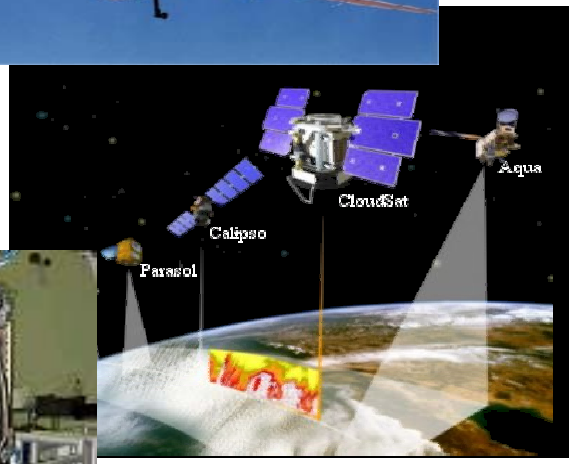
- Single craft → Constellations
  - Earth-Sun connection
  - Interferometery
  - Multi-wavelength astronomy
  - Coordinated orbital, aerial, and surface exploration
  - Leads to a need to for coordinated control, and a need to decrease operations costs and increase reliability





Autonomous Systems Drivers – Aeronatuics

- Unmanned Air Vehicles
  - Safe and secure operations of UAVs within the national airspace.
  - Long duration, earth observation missions.
- Vehicle Safety
  - Ability to ensure safe operation of commercial and military aeronautics vehicles under off-nominal conditions.
- National Airspace
  - Automated decision making to the throughput of the national



Autonomous Systems Drivers – General Requirements

- **Next generation mission operations enabling reduced cost, reduced risk, and increased throughput:**
  - Improved full-system (vehicle+human) situational awareness
  - Distributed science planning and mission operations enabling large-scale world-wide collaboration (among 100+ scientists and engineers)
  - Continuous monitoring and management of risks & risk mitigation plans
  - Adjustable levels of required human decision-making
  - Integration of mission design with operations and analysis
- **Real-time decision-making and closed loop control enabling robustness under a wide variety of environmental conditions:**
  - Rapid response systems/Reflexive behaviors
  - Rapid fault detection, isolation, recovery, and reconfiguration
  - Fusion of multiple sensors into a full system state estimate
  - Assured execution of critical sequences
- **Multi-agent and human-agent collaboration on complex tasks:**
  - Multivehicle/multispacecraft coordination
  - Multi-mission event response (e.g. Sensor Web)
  - Distributed sensing/surveying
  - Robotic In-Space Construction
  - Human-Robotic cooperation/collaboration/coordination including human-directed robotic construction, and space science activities
- **Long term and distant operation (S,Y):**
  - Autonomous science (on-board)
  - Persistent presence for exploration
  - Demonstrably robust, survivable systems
  - Validation of on-board decision-making by transparent migration from ground to flight during the mission

Computing Systems – Mission Drivers

NASA missions are critically dependent upon computing systems to provide functionality that enables the missions

Space-qualified Computing

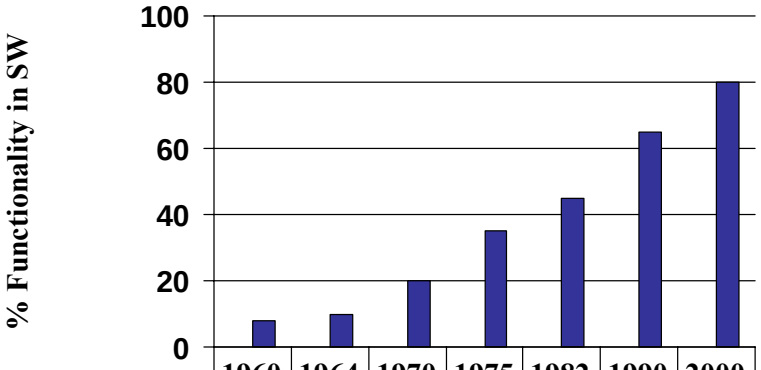
- Computer platforms that can operate within the space environment.

Dependable Computing Architectures

- Computing architectures including proces networking and storage for robust operati

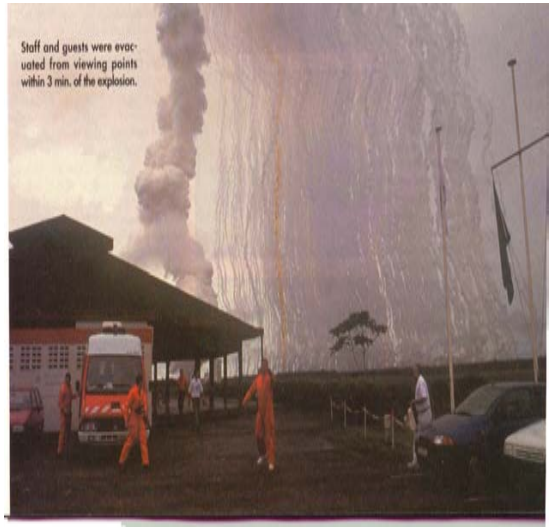
Robust Software Systems

- Ability to develop software systems relial and in a cost effective manner.



	1960	1964	1970	1975	1982	1990	2000
System	F4	A7	F11	F15	F16	B2	F22
%SW Funct	8	10	20	35	45	65	80

Software is a Risk Factor for NASA Missions: Reliability, Cost, Schedule



Software Related Failures

- Aug 27, 1998 failure of the Boeing Delta 3
- April 30, 1999 loss of a Titan I (cost $1.23 billion)
- 1999, three successive Titan IV mission failures
- Mars Polar Lander
- Mars Climate Orbiter

Some problems:

- We are very good at building complex software systems that work **95% of the time---but, we do not know how to build complex software systems that are ultra-reliable.**
- Quote from Mike Sander Project Manager for MSL: Question: How do you know when you have tested the software enough? Answer: "It is time
- to launch the spacecraft."
- Cost and schedule drivers are high for aerospace software, yet risk has not been controlled.
- ISS has over a 1000 work-around procedures for operators to follow to adapt and adjust to software problems.

Why is this a problem?

- Computing systems and software are system-level capabilities.
- Integrate functionality that cuts across the entire system creating complex couplings between different sub-systems.
- Software and computing systems is where we implement our Concept of Operations which depends upon the complex interaction of the systems-of-systems supporting the mission.
- Software and computing systems provide you with flexibility allowing you to adapt and adjust to changes in the mission requirements.
- NASA has long lead time missions, but computing technologies evolve at a much greater rate in industry making it difficult to adapt to these changes.
- Operation of systems and platforms over extended periods of time (e.g. Station or Shuttle) require a software architecture that can evolve and adapt to the changing requirements and technologies. However, modifying and changing software can be very costly.

	1. High-energy power and propulsion	2. In-space transportation	3. Advanced telescopes and observatories	4.Communication & Navigation	5. Robotic access to planetary surfaces	6. Human planetary landing systems	7. Human health and support systems	8. Human exploration systems and mobility	9. Autonomous systems and robotics	10. Transformational spaceport/range technologies	11. Scientific instruments and sensors	12. *In situ* resource utilization	13. Advanced modeling, simulation, analysis	14. Systems engineering cost/risk analysis	15. Nanotechnology
1. High-energy power and propulsion									Enabling						
2. In-space transportation									Enhance						
3. Advanced telescopes and observatories									Enabling						
4. Communication & Navigation									Enhancing						
5. Robotic access to planetary surfaces									Enabling						
6. Human planetary landing systems									Enhancing						
7. Human health and support systems									Enabling						
8. Human exploration systems and mobility									Enabling						
9. Autonomous systems and robotics										Enhancing	Limited synergy	Enabling	Enhancing to us	Enhancing to us	Enancing to us
10. Transformational spaceport/range technologies															
11. Scientific instruments and sensors															
12. *In situ* resource utilization															
13. Advanced modeling, simulation, analysis															
14. Systems engineering cost/risk analysis															
15. Nanotechnology															

Same element

Critical Relationship (dependent, synergistic, or enabling)

Moderate Relationship (enhancing, limited impact, or limited synergy)

No Relationship

Relationship with Other Roadmaps

Autonomous Systems and Robotics		**Other Capability Roadmap**	
Sub-Topic or Subsidiary Capability	**Capability Flow & Criticality**	Sub-Topic or Subsidiary Capability	Nature of Relationship
Integrated Systems Health Management	→	1. High-energy power and propulsion	Real time monitoring and intervention to manage the health and operation of the nuclear power or propulsion systems
Integrated Systems Health Management	→	2. In-space transportation	Health management and control
Robotic Systems, Human Machine Interaction	→	3. Advanced telescopes and observatories	Robotic agents for construction, inspection, maintennacne and repair; Autonomous control is enhancing
Planning and Execution and Integrated System Health Management	→	4. Communication & Navigation	Autonomous control for navigation
All elements	→	5. Robotic access to planetary surfaces	Robotic mobility enabling to planetary access; autonomy for EDL including both decision making and machine vision and perception
Machine perception, planning and execution, integrated system health management	→	6. Human planetary landing systems	Health management and on-board decision making to augment human control
Planning and execution, human-machine interaction, integrated system health management	→	7. Human health and support systems	Autonomous control for advanced life support, smart space suites to augment human performance and interaction with robotic assistants
All elements	→	8. Human exploration systems and mobility	Robotic systems provide needed mobility and dexterity and Autonomous reasoning required for crew-centered operation

Autonomous Systems and Robotics		Other Capability Roadmap	
All elements	↔	11. Scientific instruments and sensors	Advanced sensors provide critical information for robotic systems. Autonomous systems and robotics may provide some capability as you develop embedded reasoning into sensors. Concept of large distributed sensing systems can create significant overlap and
Integrated Systems health Management and Planning and Execution	→	12. *In situ* resource utilization	Autonomous control and health mangement of ISRU devices
Robotic systems	←	13. Advanced modeling, simulation, analysis	Modeling and simulation critical for design and understanding of complex systems
	←	14. Systems engineering cost/risk analysis	Assist in understanding system wide implcations of autonomous and robotic assistants
Robotic systems	←	Nanotechnology	Nanotechnology leads to improved sensors and actuation, low power consumption and other capabilities to reduce size, weight, power and cost of the robotic devices. We enhance them as well since control of nano-based devices may required use of autonomous reasoning of collectives

Action Plan

1. **What is needed by the agency?**

2. **What we can expect externally?**
   - Identify commonality with commercial markets and other government agencies. Distinguish between
     - Capability commonality
     - Technology commonality
   - If capability is required by a commercial market, reasonable to expect external development. If commonality with another government agency, then we have a shared responsibility to develop the capability.
   - What does NASA need to do to leverage external investment?

3. **What should NASA invest in?**
   - Identification of priorities based upon needs and potential for external investment.
   - Estimate appropriate level of investment and what you get for each level.

4. **How should NASA invest?**
   - Advice in programmatic structure and mechanism for implementation to ensure impact.

What I need from you?

Capability Requirements:

- What do you see are the driving requirements for ASR&C capabilities to enable NASA's mission.

Critical Technologies:

- What technologies are critical for delivering these capabilities?
- What other investments exist that are relevant?
- What is the best way to project when certain capabilities will be available?

Impact:

- What needs to be done to ensure impact of these technologies on NASA's mission?

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