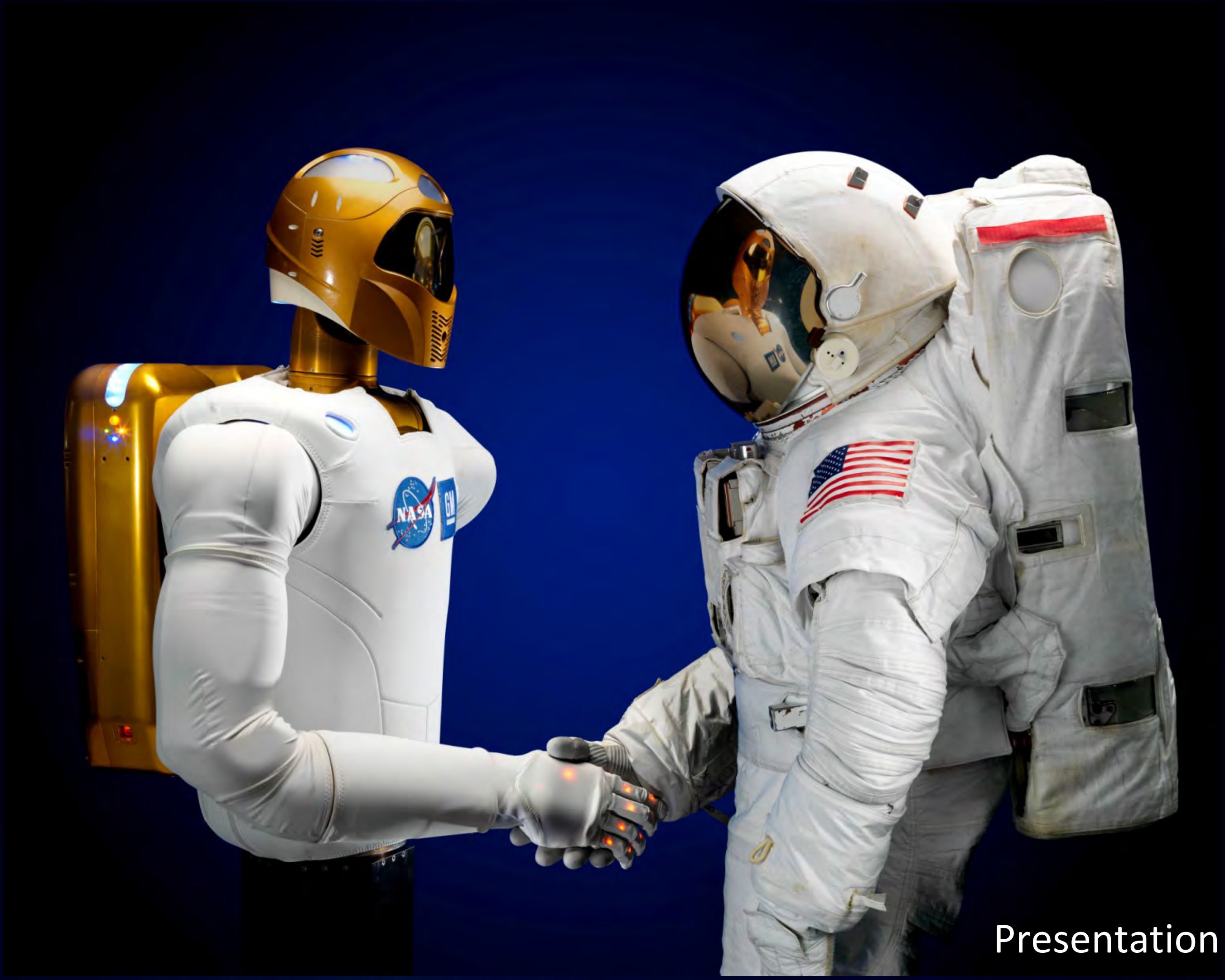
Robotics and Autonomous Systems



Presentation to the NAC

Dr. Rob Ambrose

April 2013

NASA has Consolidated Robotics R&D in OCT and STMD

NASA created the Office of the Chief Technologist (OCT) in 2010, serving as the NASA Administrator's principal advisor and advocate on matters concerning agency-wide technology. Dr. Mason Peck is NASA's Chief Technologist.

http://www.nasa.gov/offices/oct/about_us/bios/oct_peck_bio.html

NASA's Space Technologies Mission Directorate develops and demonstrates advanced space systems concepts and technologies enabling new approaches for existing programs and making future missions possible. Dr. Mike Gazarik is the STMD Associate Administrator.

http://www.nasa.gov/offices/oct/about_us/bios/oct_gazarik_bio.html

STMD Has named Principal Investigators for technology domains, including Dr. Rob Ambrose who serves as the PI for Robotics & Autonomous Systems.

http://gcd.larc_nasa.gov/about/team/principal-investigators/rob-ambrose/

Future human exploration space missions will include teams of crew and robots, working with highly autonomous spacecraft.

Systems will provide crew independence from Earth as they travel into deep space.

Systems will also work seperate from crew, providing unique capabilities.

Roles will include:

Precursors that go before humans.
Assistance robots and systems that work with crew.
Caretakers that work on crew "tended" vehicles.

It is not human vs. machine, but humans with machines.

Robotics and Autonomous Systems Approach

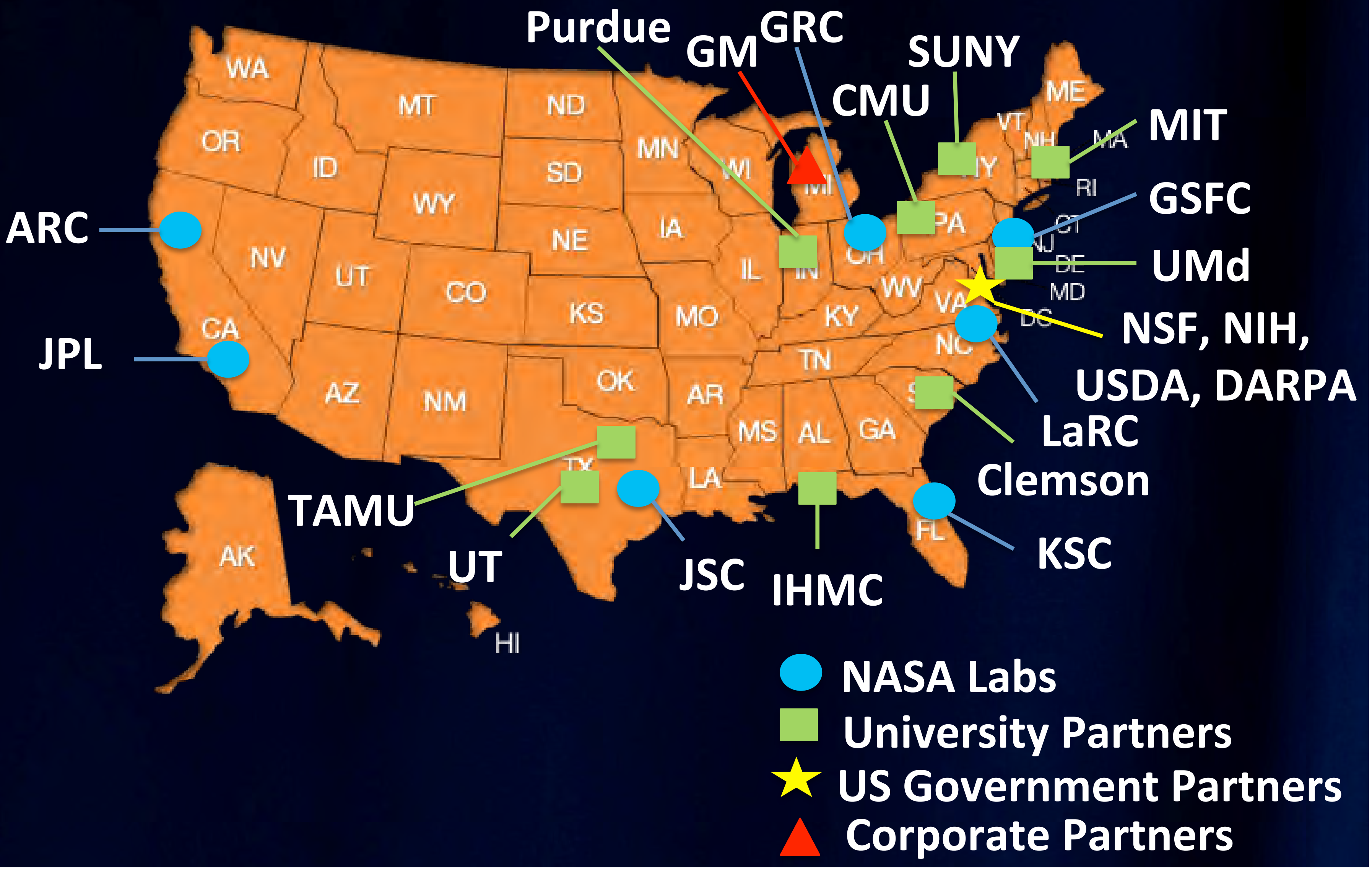
- NASA develops and matures prototype systems, subsystems, and component technologies in advance of key agency decision points
  - Target TRL 5-6 prior to program infusion

- Supports all potential missions in capability driven framework
- Infusing robotics and autonomous systems technology into space missions by leveraging national and international efforts that build upon:
  - Commercial partnerships
  - Space Act Agreements
  - Other government agencies (NSF, NIH,USDA, DARPA, NRL, VA, etc.)
  - SBIR/STTR
  - University Research
  - National Robotics Initiative

- Work with human exploration architecture communities to address key technical challenges in support of a variety of design reference missions (ISS and beyond)
- Work with the science mission directorate on roadmaps and once a decade surveys (Spirit, Curiosity and beyond)

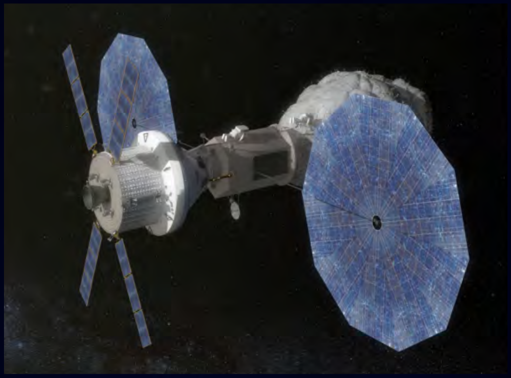
NASA Labs and Partners

(Working in Robotics and Autonomous Systems Technology)



How Will NASA Use Robots?

Capabilities Like:
Asteroid Capture
Access Extreme Terrain
Autonomous Control
Sample Processing



Precursors

Asteroid Sampling
Skylight Exploration
Search for Life on Mars

Capabilities Like:
Spaccraft Grappling
Crew Mobility/Stabilization
Logistics / House Chores
Repair and Inspection

Assistants

Space Station
Asteroid Missions
Deep Space

Capabilities Like:
Caretaker for Facility
Repair and Servicing
Contingency Ops
Long Term Science

Caretakers

Mars Missions
Asteroid Missions
Deep Space

Robotics, Tele-Robotics and Autonomous Systems Roadmap

TA4.1 Sensing & Perception

- TA4.1.1 3-D Perception
- TA4.1.2 Relative Position & Velocity Estimation
- TA4.1.3 Terrain Mapping, Classification & Characterization
- TA4.1.4 Natural & Man-made Object Recognition
- TA4.1.5 Sensor Fusion for Sampling & Manipulation
- TA4.1.6 Onboard Science Data Analysis

TA4.2 Mobility

- TA4.2.1 Extreme Terrain Mobility
- TA4.2.2 Below-Surface Mobility
- TA4.2.3 Above-Surface Mobility
- TA4.2.4 Small Body / Microgravity Mobility

TA4.3 Manipulation

- TA4.3.1 Robot Arms
- TA4.3.2 Dexterous Manipulators
- TA4.3.3 Modeling of Contact Dynamics
- TA4.3.4 Mobile Manipulation
- TA4.3.5 Collaborative Manipulation
- TA4.3.6 Robotic Drilling & Sample Processing

TA4.4 Human-Systems Int.

- TA4.4.1 Multi-Modal Human-Systems Interaction
- TA4.4.2 Supervisory Control
- TA4.4.3 Robot-to-Suit Interfaces
- TA4.4.4 Intent Recognition & Reaction
- TA4.4.5 Distributed Collaboration
- TA4.4.6 Common Human-Systems Interfaces
- TA4.4.7 Safety, Trust, & Interfacing of Robotic/Human Proximity Operations

TA4.5 Autonomy

- TA4.5.1 Vehicle System Management & FDIR
- TA4.5.2 Dynamic Planning & Sequencing Tools
- TA4.5.3 Autonomous Guidance & Control
- TA4.5.4 Multi-Agent Coordination
- TA4.5.5 Adjustable Autonomy
- TA4.5.6 Terrain Relative Navigation
- TA4.5.7 Path & Motion Planning with Uncertainty

TA4.6 Autonomous Rendezvous & Docking

- TA4.6.1 Relative Navigation Sensors (long-, mid-, near-range)
- TA4.6.2 Relative Guidance Algorithms
- TA4.6.3 Docking & Capture Mechanisms/ Interfaces

TA4.7 RTA Systems Engineering

- TA4.7.1 Modularity / Commonality
- TA4.7.2 Verification & Validation of Complex Adaptive Systems
- TA4.7.3 Onboard Computing

Key Challenges

New approaches for extreme terrain (NRC Review of OCT Roadmaps, top 16 challenges overall for NASA)

Approaches to deal with time delay for teleoperation

Dexterous manipulation and system autonomy to reduce crew time and support from ground.

Improved systems performance- mass, power, volume and radiation tolerance.

Improved ability to rapidly adapt software systems to new tasks/operations

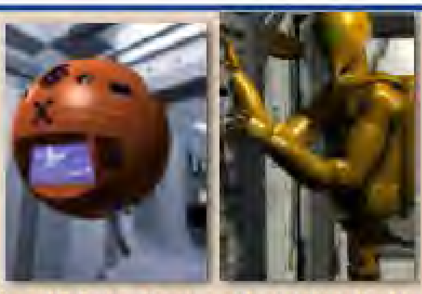
Sensing and Perception Challenges (Tele-robot ics)

A STATUS QUO

How do we safely use human-robotic partnerships to increase productivity, reduce costs, and mitigate risks?

- Modern industrial robots are unsafe for human proximity ops
- Robonaut ground tested ~ TRL 4

B NEW INSIGHT



Use ISS to test and evaluate human-robot teaming

- Test approaches for in-space safe human interactions with robots
- Remotely operate robotic systems in-space and simulate from-space control

C

OBJECTIVES:

- Integrate mobility and dexterous manipulation with human team
- Evaluate human productivity, workload & performance metrics
- Evaluate impact of microgravity on operator control ability

HOW IT WORKS:

- Test human-safe robots (R2) in 0g conditions w/ crew (on ISS)
- Test free-flyer ops on ISS (Spheres)
- Measure robot & crew productivity, with different control modes: tele-op, interactive & autonomous
- Operate with time-delay to simulate Earth, Lunar, Mars, & NEO ops
- Demonstrate multi-robot & multi-human (ground/in-space) teams

ASSUMPTIONS & LIMITATIONS:

ISS location and resources

- COTS computing, web browser, sufficient bandwidth (counter-force feedback) and latency for interactive control through communications link.

D QUANTITATIVE IMPACT

What will the observations / tests reveal?

- New approaches to robot safety that are needed for interaction
- Issues related to operating robots within crew vehicle and in μ-gravity & confined work spaces
- Testing of workload division and sharing between crew & robots
- Data to trade ground control vs. space-based control

E END-OF-PHASE GOAL

- Demo and ops of Robonaut human safe robots on ISS
- Demo and ops of Spheres free flyer on ISS
- Demo of remote human robot ops

Efficient Human-Robot Teams can be a technology driver for deep space Exploration

Mobility Challenges

STATUS QUO

- Simplified Aid For EVA Rescue (SAFER) - *single fault tolerant, for emergencies only*
- Mars rovers Opportunities, Spirit & Curiosity - *limited range, limited mobility: canyons, crates, volcanoes, volcanic tubes and cliffs inaccessible*
- Apollo Lunar Roving Vehicle (LRV) - *limited range, EVA exploration*

NEW INSIGHTS

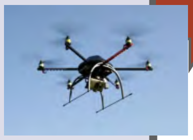
- Increase in specific power & density of batteries is enabling mobility
- Software and computing allow for multiple layers of redundancy and safety for robots to be trusted
- New sensors and algorithms are providing robust and safe operation in complex worlds
- Precursor robots that arrive ahead of crew enable new missions
- Unique approach of teaming main robot with small flyer or payload launcher with ballistic probes

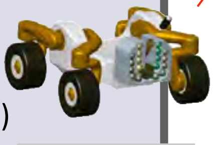
PROBLEM / NEED BEING ADDRESSED

Humans are more productive through use of robots and human-robot teaming. Robotic systems need advancements to gain trust as valuable members of the team. Systems for crew and cargo mobility lack the range and mobility (TA4.2) to explore beyond flat terrain near their landing site. * Astronauts lack a reliable means of transportation during EVAs (TA7.3.1) for future in-space missions, and are limited to crawling on truss or riding robotic arm for EVA on ISS.

AREAS OF EMPHASIS:

- Current mobility developmental portfolio includes:
  - 1st gen prototype of next generation EVA jetpack
  - Supply test articles for ISRU and Desert RATS field tests
  - Development of novel robotic teams that combine wheeled and ballistic/flying mobility
  - Systems that enable testing of crew and robotic in simulated reduced gravity (micro gravity, Mars and Lunar)
  - Develop approaches for dealing with autonomous planetary surface navigation over distances greater than 1 km with limited/no communications
  - Develop approaches and demonstrate rover extraction from very soft soil





QUANTITATIVE IMPACT

- Increase in-space EVA mobility option from 2 to 3 with EVA jetpack
- Increase number of Centaur 2 base payloads by > 2
- Add sensing and software to increase mean time between user intervention when driving to > 1km
- Vastly extend exploration range with flyers and ballistic probe launcher

TECHNICAL GOALS

- ***Add new NASA crew and robotic mobility capabilities***
- ***Mature mobility systems, subsystems and components to TRL 5-6 prior to infusion***
- ***Ready for Key Decision Points on orbital, asteroid and planetary missions***

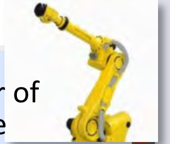
Manipulation Challenges

STATUS QUO

Robonaut 2:
IVA robot on ISS
SPDM/SSRMS:
EVA robots on ISS
Mars assets:
Opportunity, Spirit, Phoenix & Curiosity:
Sampling arms
Commercial:
Heavy Equipment (CAT, Deere, Oshkosh, etc), Robotic assembly (non-US)







NEW INSIGHTS

- To be a valuable member of the team, robots must be capable, safe and trusted
  - Software and computing allow for multiple layers of redundancy and safety
  - New sensors and algorithms are providing robust and safe operation in complex worlds
- LCROSS mission provided evidence for significant amounts of cold trapped volatiles near the Moon's south pole

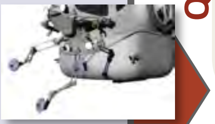
PROBLEM / NEED BEING ADDRESSED

Humans are more productive through the use of robots and human-robot teaming. NASA missions require advanced manipulation capabilities to offload cargo and assist crew (TA4.1, 4.3) and to find and acquire in-situ resources (TA7.1)

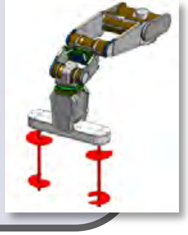
AREAS OF EMPHASIS:

Current manipulation developmental portfolio includes:

- Develop grappling and dexterous arms for the Multi-mission Space Exploration Vehicles (MMSEV)
- Development of long reach manipulators
- Asteroid anchoring tools
- Excavation tools, buckets, booms, approaches, trenching tools







QUANTITATIVE IMPACT

- Increase number of arms on second generation MMSEV to greater than 2
- Increase range of "asteroid" surface properties that may be anchored to by 50%
- Decrease operators required for excavation with Centaur 2 by 1.
- Provide capabilities to NASA that don't currently exist

TECHNICAL GOALS

- **Add new crew and robotic mobility capabilities to NASA**
- **mature handling systems, subsystems and components to TRL 5-6 prior infusion**
- **Be ready for Key Decision Point on orbital, asteroid and planetary missions**
- **Evaluate ideas being debated by architecture communities**

Human Systems Interaction Challenges

STATUS QUO

SPDM/SSRMS ground control/IV control: *slow paced*

Roving on Mars: *plans uploaded daily (every Sol)*

Factory automation:*lack of general tasks*

DARPA challenges: *automated control over mostly even terrain*

Video gaming engines: *lots of potential*

NEW INSIGHTS

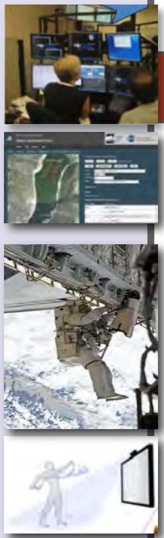
- To be a valuable member of the team, robots must be capable, safe and trusted
  - Software and computing allow for multiple layers of redundancy and safety for robots to be trusted
- Increwed and precursor missions, robotic systems will need to have autonomous, supervised and teleoperated control modes.
  - Many missions will allow for interactive, but not real-time control allowing to get more work done in a show period

PROBLEM / NEED BEING ADDRESSED

Humans are more productive through the use of robots and human-robot teaming. NASA missions require the ability to control and operate robotic systems from ground, teleoperated and shoulder-to-shoulder with crew advanced (TA4.4, TA4.5)

AREAS OF EMPHASIS:

- Current human systems interaction developmental portfolio includes:
  - Develop hands-free interface to EVA jetpacks
  - Controlling Centaur 2 base remotely during In-situ resource utilization (ISRU) field testing
  - Providing ground data systems to present, share and archive science and mission data
  - Develop ground data tools for high tempo operations such as volatile prospecting in permanently shadowed regions
  - Develop software infrastructure for controlling Space robotic systems. Engage standards community to move toward Intl standards for robot control
  - Develop natural interfaces and intent recognition for teleoperation



QUANTITATIVE IMPACT

- Reduce hands needed to fly EVA jetpack to zero
- Provide ground data systems for 1 or more NASA analog
- Remotely drive Centaur 2 base greater than 1 km with minimal comm
- Progress HRS robot command/control software towards international standard
- Provide capabilities to NASA that don't currently exist

TECHNICAL GOALS

- **Add new crew and robotic mobility capabilities to NASA**
- **Mature handling systems, subsystems and components to TRL 5-6 prior to infusion**
- **Be ready for Key Decision Points on orbital, asteroid and planetary missions**
- **Evaluate ideas being debated by architecture communities**

Autonomy Challenges

STATUS QUO

- Current State of the Art:
- Spacecraft habitat automation an ‘all or nothing’ proposition (whether commanded from ground or via vehicle system)
- Today’s spacecraft habitat commanded by people soley from ground
- 300k commands sent to ISS per year
- ISS onboard systems ill suited to automation by crew, which will be required for future manned missions far from Earth

NEW INSIGHTS

- Deep Space Habitats will be constrained by light-time delays in communications, requiring on-board automation.
- Spacecraft habitat will be designed to allow crew to automate vehicle function as they require or desire, reducing dependence on ground.
- Advanced fault management techniques integrated with crew autonomy will increase vehicle safety.
- Integrated Autonomy and ISHM capabilities enable new modes of operation for crewed spaceflight.

PROBLEM / NEED BEING ADDRESSED

Crewed mission beyond LEO will require integrated onboard autonomy and robust onboard capability.

AREA OF EMPHASIS:

- Develop software to allow human spaceflight oprations to be automated to any degree desired by crews.
- Integrate several technologies on a similar development path to demonstrate procedure and command generation, model verification, fault detection, and automation.
- Demonstrate crew autonomy in a sequence of relevent environments, from high-fidelity testbeds through a spaceflight demo.
- Automation will be demonstrated in ISS Flight Control Room (FCR), Space Station Training Facility, and finally evaluated by crew onboard ISS.
- Activity includes system modeling, model verification, adaptation of diagnostics to the system models, procedure automation, and dynamically reconfigurable autonomous operation and recovery.
- Provide to ISS an ability to automate vehicle functions

QUANTITATIVE IMPACT

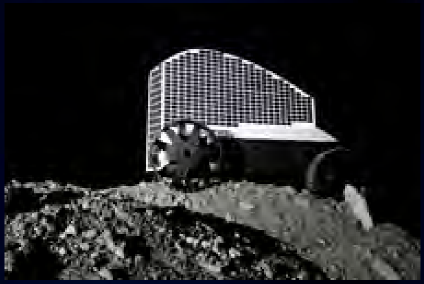
- Reduced dependence on Ground for distant crewed missions.
- Increased crew flexibility, efficiency and safety
- Authority of tasks shared between vehicle and small crew
- Demonstration of on-board fault management capability working with goal-directed autonomy

TECHNICAL GOALS

- Critical Technologies @ TRL 5-6
- Proof-of-concept in spaceflight environment
- Crew-adjustable autonomy
- Diagnostic models
- Integrated system

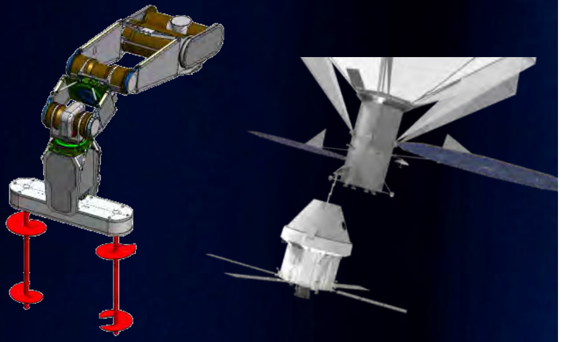
Provide proof-of-concept integrated systems required for advanced habitat autonomy.

Other Challenge: Extreme Terrain*



Lunar Precursor Missions

Non Geometric Hazards
Active Suspension
Novel Mechanisms



Asteroid Missions

Robotic Anchoring
Robot Grappling and Sampling
Astronaut Jet Packs

Mars Missions

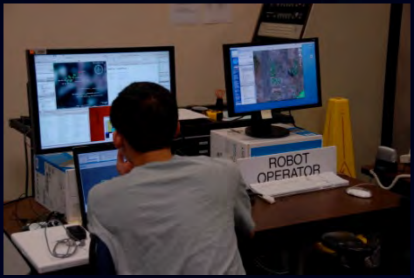
Visual Odometry
Rover Self Extraction

*Listed by NRC OCT Roadmap Review as one of the agency’s Top 16 Challenges overall.

Other Challenges

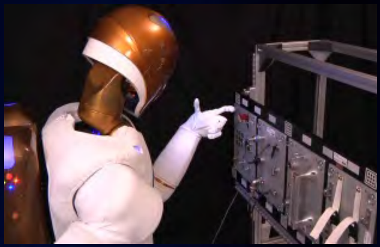
Time Delayed Teleopration

Task Level Commands
Monitor Progress
Predictive Displays



Robot Dexterity

Robot Mobile Navigation
Robot Dexterous Manipulation
Safety (Alone and Near People)



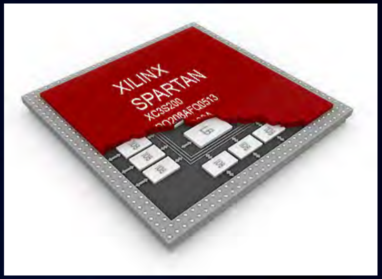
System Automation

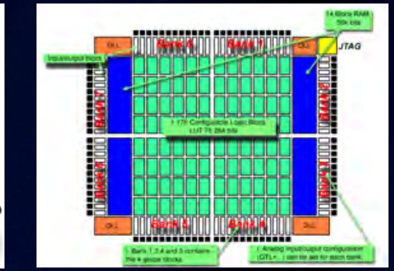
Vehicle System Automation (FDIR)
Reduced Crew Time
Reduced Ground Time

Other Challenges

Performance

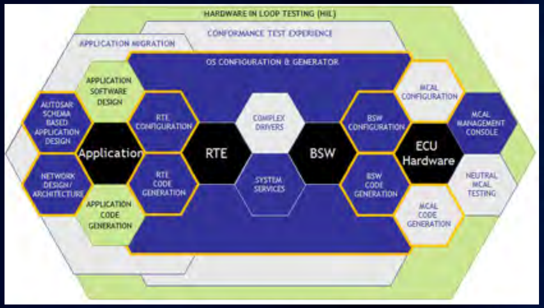
- *Reduced Mass & Volume*
  - *Advanced Batteries*
  - *New Materials*
- *Radiation Tolerance*
  - *FPGA Developments*
  - *Beam Testing*





Rapid Software Adaption

- *System Modelling*
  - *End-to-End System Models*
  - *Vehicle has Onboard Sim*
  - *Model Validation*
- *Software Tools*
  - *Code Generation*
  - *Verification and Validation*
  - *Electronic Procedures*



National Robotics Initiative (NRI)

NSF, NASA, NIH, USDA

President Obama, June 2011, NREC

National Robotics Initiative (NRI)

Pipeline Apporach

For decades NASA has been a strong supporter of educational robotics outreach, and is backing robotics competitions that engage tens of thousands of children each year. We believe that one of these young people will invent and build the next big thing for the US.

http://robotics.nasa.gov/

NSF, NASA and other agencies are partnering on a joint solicitation to provide grants for research in new aspects of robotics technology. Each agency has specific interests in research topics with in the NRI's co-robotics theme.

http://www.nsf.gov/pubs/2011/nsf11553/nsf11553.htm

NASA is looking for partnerships with companies that have independent research programs and share an aligned vision for products and capabilities sought by NASA. One example is the Robonaut partnership with General Motors.

http://robonaut.jsc.nasa.gov/default.asp

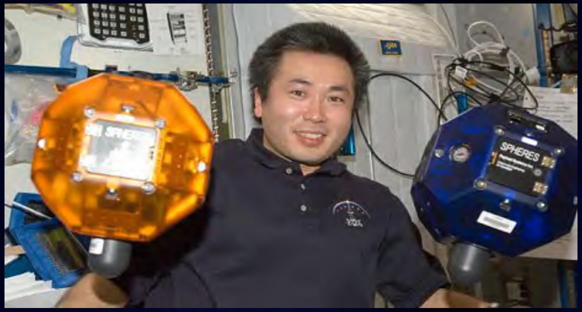
NASA’s Recent NRI Awards

1	“Toward Human Avatar Robots for Co-Exploration of Hazardous Environments”	Institute of Human Machine Cognition	J. Pratt	Pensacola Florida
2	“A Novel Powered Leg Prosthesis Simulator for Sensing & Control Development”	MIT	H. Herr	Cambridge Massachusetts
3	“Long-range Prediction of Non-Geometric Terrain Hazards for Reliable Planetary Rover Traverse”	CMU	R. Whittaker	Pittsburgh Pennsylvania
4	“Active Skins for Simplified Tactile Feedback in Robotics”	Univ. of Maryland	S. Bergbreiter	College Park Maryland
5	“Actuators for Safe, Strong and Efficient Humanoid Robots”	Purdue	S. Pekarek	West Lafeyette Indiana
6	“Whole-body Telemanipulation of the Dreamer Humanoid Robot on Rough Terrains Using Hand Exoskeleton (EXODREAM)”	Univ. of Texas	L. Sentis	Austin Texas
7	“Long, Thin Continuum Robots for Space Applications”	Clemsom	I. Walker	Clemson South Carolina
8	“Manipulating Flexible Materials Using Sparse Coding”	State University of New York, Buffalo	R. PLatt	Buffalo New York

Upcoming Robotics Activities

Robonaut Legs

Zero Gravity Climbing
Launches to ISS on Space X-3 Sept 2013



Smart Spheres

Integrates Samsung Nexus
Conduct ISS Interior Survey

X1 Exoskeleton

Wearable Robotics
Exercise and Dynamometer Tests on ISS

DARPA Robotics Challenge

Building a Hero
Mobile Manipulation for Space

Summary

- Robotics and autonomy are key drivers for BLEO exploration
  - No crew for extended periods of time, or precursors
  - Maximize crew time for unique science operations
  - Pre-placement of hardware and maintenance of systems
- Technical challenges exists in sensing and perception, mobility, manipulation, human systems interaction, radiation, extreme environments, and terrain
- NASA making steady progress utilizing nationwide robotics and autonomous systems efforts to achieve TRL 5-6 prior to Program infusion
  - Leverage industry, academia, and other government agencies
- Mars and ISS operational environments utilized today as pathfinder for future human robotics and autonomy