Innovation in Space Robotics

Technology transfer and open source

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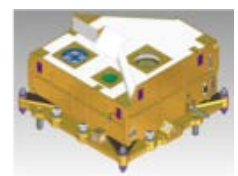
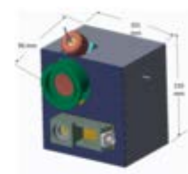
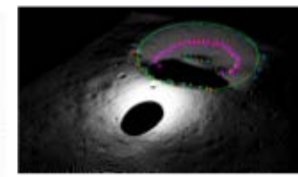
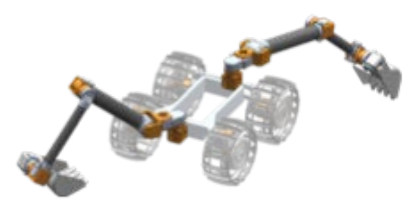
NASA space robotics strategy

Objectives

- Grow & sustain the **space economy**
- Respond to demand from **commercial** space, **human exploration**, and **science** in/from space
- Create and accelerate a community of **academia**, **government**, and **industry** to develop technology

Approach

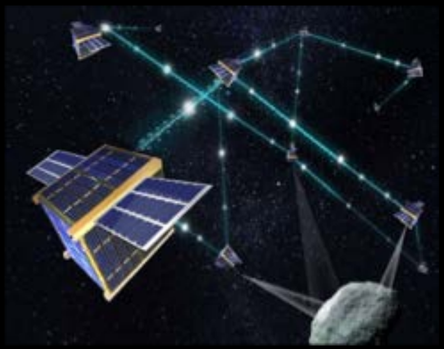
- **Open framework** – enable sustained development of modular, interoperable, and reusable technology by many
- NASA develops prototypes to break barriers and **reduce technical risk**
- Establish **collaborative projects** to integrate technology into flight missions



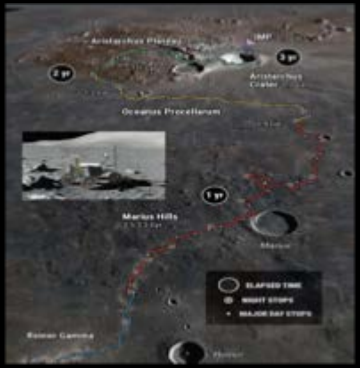
Future space robotic systems

AUTONOMOUS MULTI-SPACECRAFT SYSTEM FOR DISTRIBUTED SCIENCE



AUTONOMOUS FAIL-ACTIVE, HIGH-TEMPO SCIENCE MISSIONS

AUTONOMOUS HIGH PROGRESS RATE SCIENCE ROVER



AUTONOMOUS CONTINUOUS LUNAR SURFACE OPERATIONS

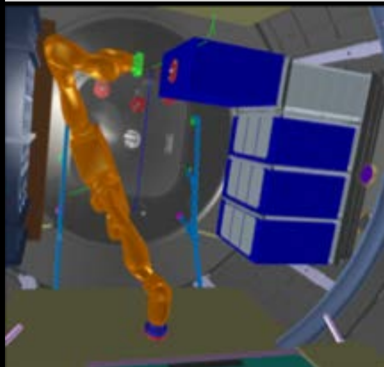
TECHNOLOGY OBJECTIVES

- **Cooperative multi-spacecraft system with efficient human teaming** for interdependent and distributed action (system operable as a single “entity”)
- **Self-adaptive and fail-active autonomy for high-tempo missions** in high-risk environments (example: guaranteed acquisition of 5 high-value samples during 20-day Europa mission)
- **High progress rate self-driving planetary rover** with cost-effective mission control (1/10 cost of current practice) and increased performance (10x productivity / time) for long range (450 km/yr) or continuous worksite operations (750 km/yr)

Note: Systems shown are not currently funded or approved, but rather reflect an envisioned future to guide mission planning and technology development.

Future space robotic systems

ROBOTIC CARETAKING INSIDE HABITATS AND SPACECRAFT



ROBOTIC EXPLORATION OF EXTREME ENVIRONMENTS

ROBOTIC CONSTRUCTION OF SURFACE INFRASTRUCTURE

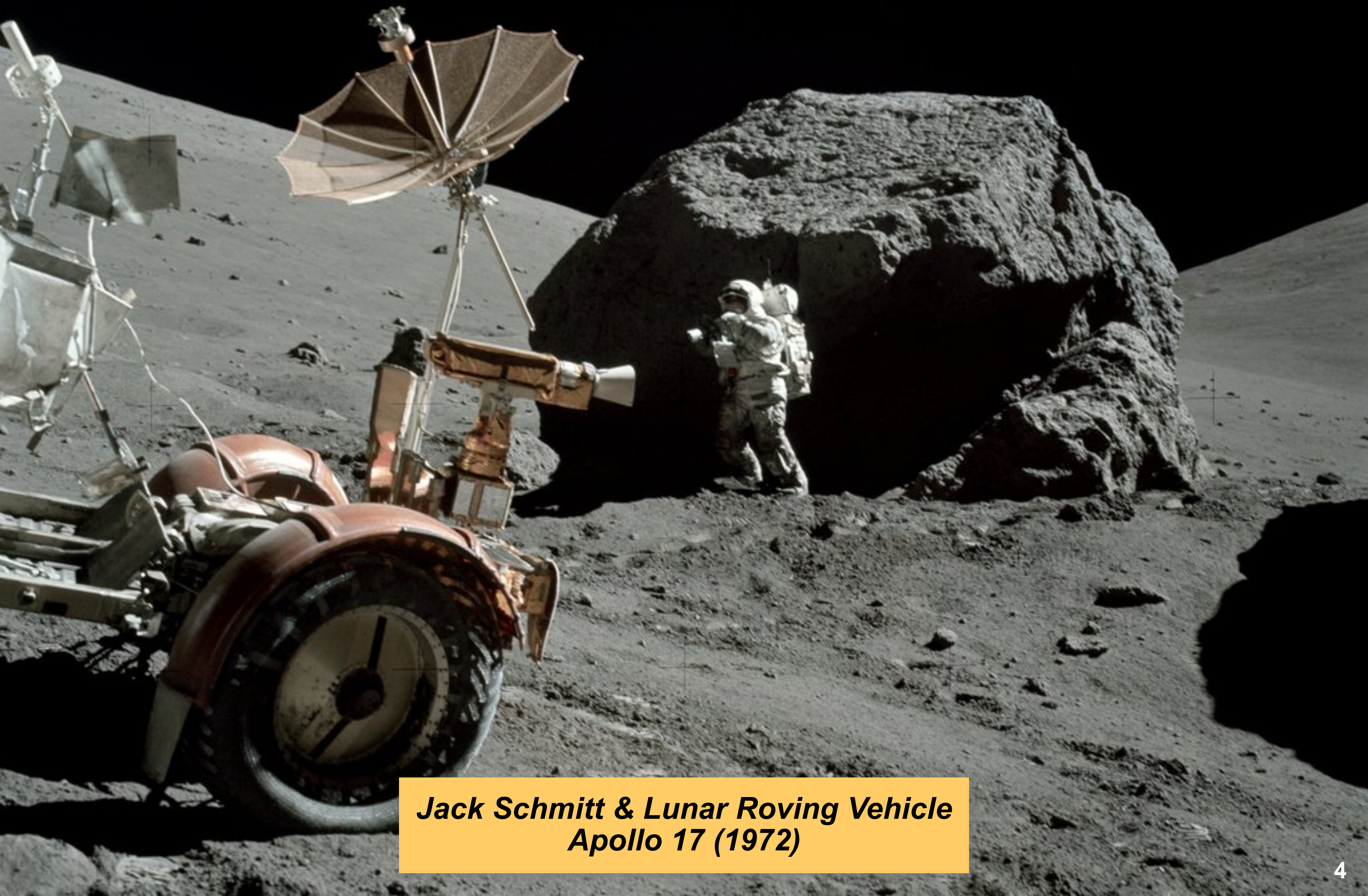
ROBOTIC RESOURCE EXTRACTION + TRANSPORT

TECHNOLOGY OBJECTIVES

- **Remotely operated intra-vehicular robotics** for maintenance and utilization (4,000+ hr/yr) of uncrewed (up to 90% time) spacecraft and surface habitats
- **Robust robot mobility for extreme access**: surfaces (5,000 km life-cycle drive), deep interiors (up to 25 km) through rock and cryogenic ice, and handling of dangerous topography (up to 90° slopes)
- **Durable, self-maintainable robotics** for heavy-duty surface work: bulk excavation (100-400 metric tons), material transport (500-600 km/yr), and surface construction (15,000 kg carrying capacity)

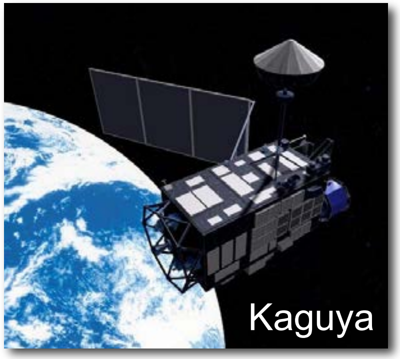
Note: Systems shown are not currently funded or approved, but rather reflect an envisioned future to guide mission planning and technology development.

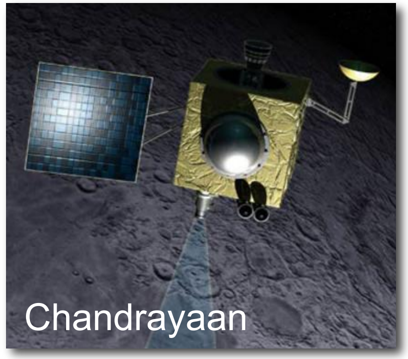
Human planetary exploration



Jack Schmitt & Lunar Roving Vehicle
Apollo 17 (1972)

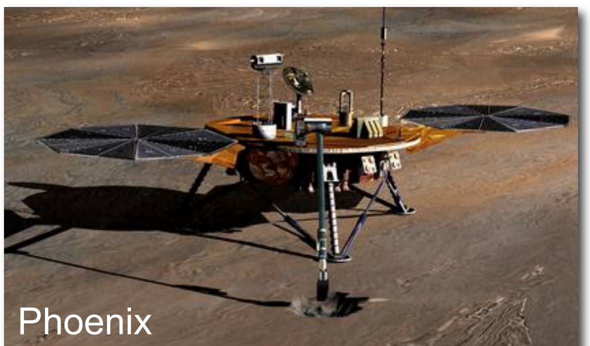
What’s changed since Apollo?


Kaguya


Chandrayaan

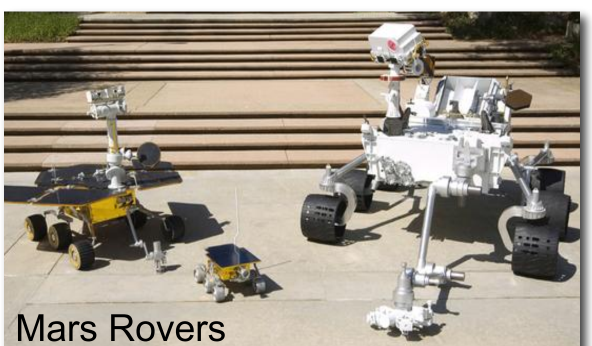

LRO


Space Station


Phoenix


Robonaut 2


LCROSS


Mars Rovers


ATHLETE, K10, Chariot

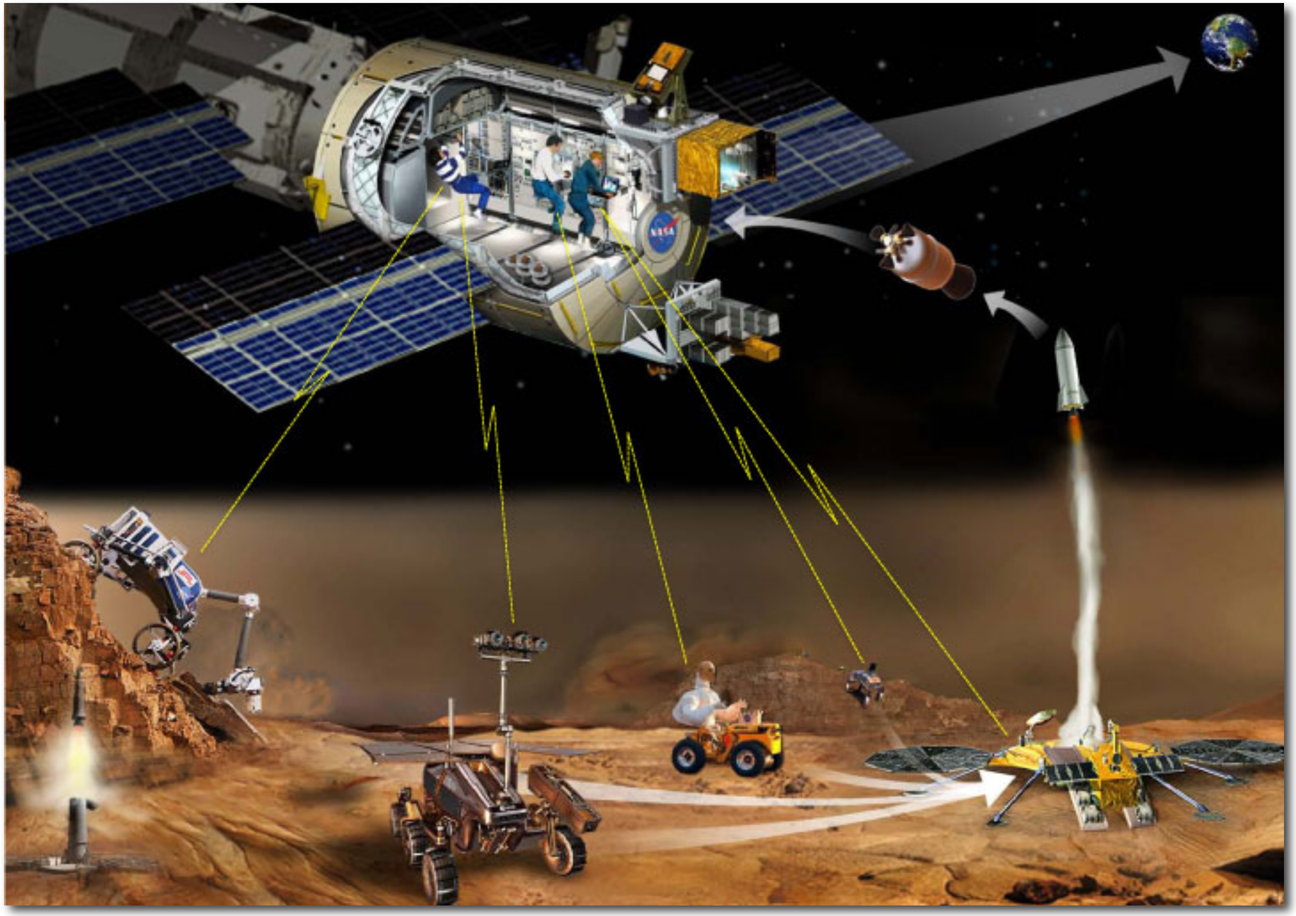
Human-robot teaming for space

Improve performance

- Humans can **remotely support autonomous robots**
- Address the many **anomalies**, **corner cases**, and **edge cases** that require unique solutions, but which are not currently practical to develop, test, and validate under real-world conditions
- Humans provide high-level guidance (not low-level control) to assist when autonomy is inadequate, untrusted, etc.

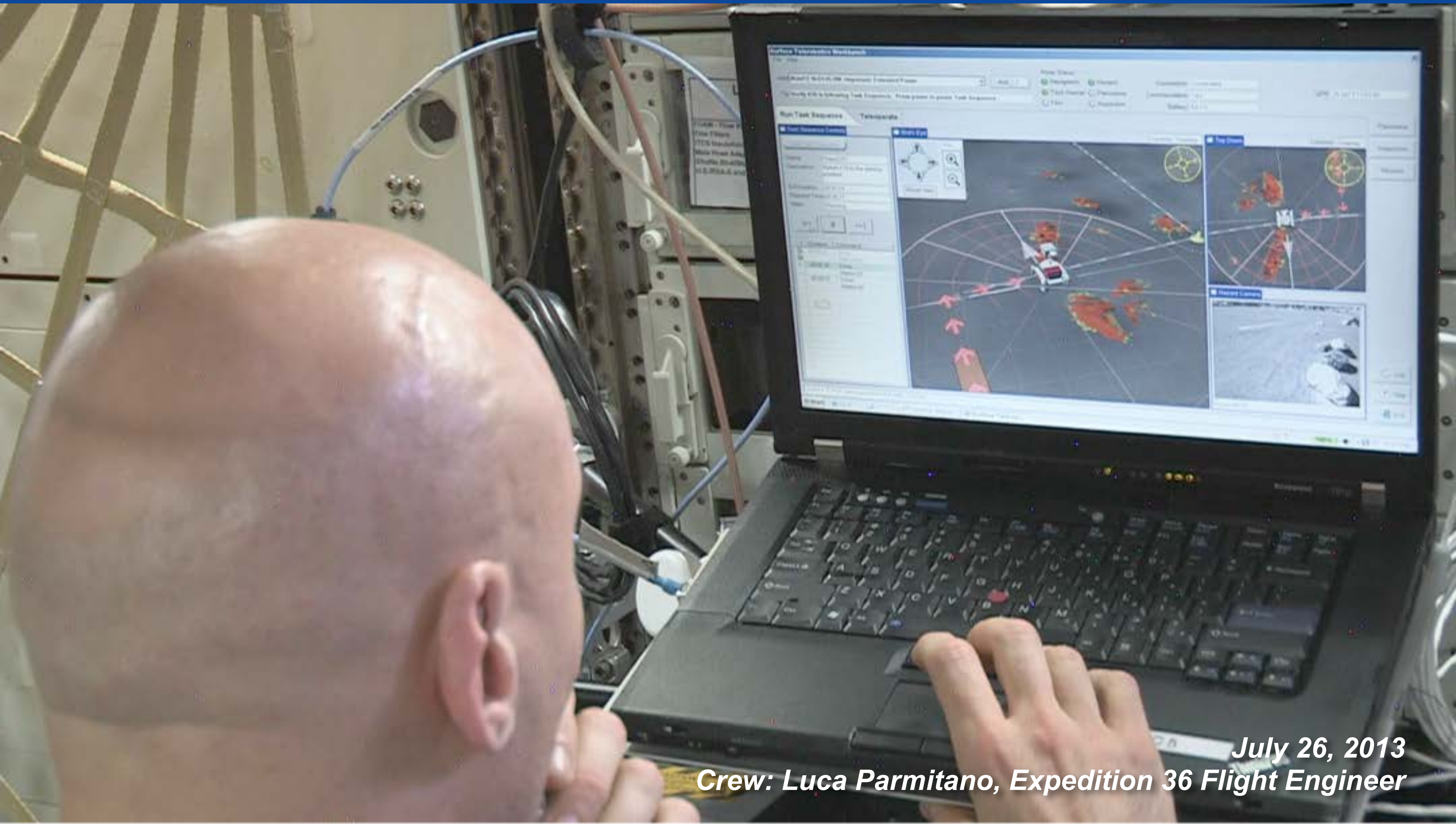
Remotely operating robot from space

Multiple space agencies have recommended that astronauts be able to remotely operate planetary rovers from orbit – *"Avatar" in real-life*



Astronaut in space / robot on Earth

Astronaut remotely helping space robot



July 26, 2013
Crew: Luca Parmitano, Expedition 36 Flight Engineer

Self-driving cars at NASA Ames

Public/private partnerships

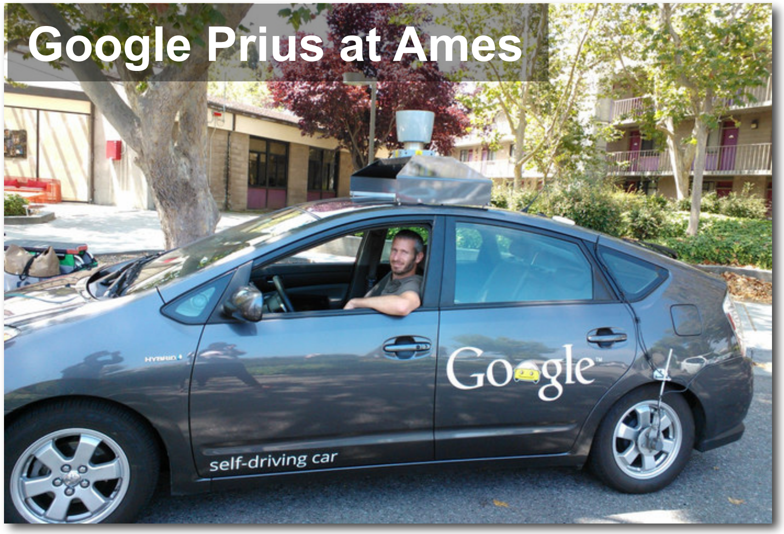
- **Google** (2014 - 15): collaborative testing of sensors and vehicles
- **Nissan** (2014 - present): cooperative software development

NASA interest

- Expand knowledge of commercial autonomous systems
- Develop protocols and best practices for testing of autonomous systems under **complex real-world conditions**
- Facilitate transfer of NASA technology

Technology maturation

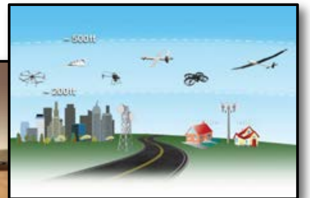
- Safe testing in urban environment
- **Leverage NASA expertise** in autonomy, robotics, safety critical systems, and rigorous testing



Google Prius at Ames

Nissan Leaf at Ames

NASA and self-driving cars



NASA Missions

Planned human-machine interaction

Natural and time delayed environments

Aerial, space, and planetary navigation

On-board and ground control autonomy

Cyber-security for "one-off" systems

…

Common Technologies

Autonomy
Advanced Planning & Scheduling Algorithms, etc.

Human-Autonomy Teaming
Robotic Supervision including Human/Robotic Interactions, etc.

Networked Operations
Remote Vehicle Management, etc.

Prognostics / Diagnostics
Including State Management, etc.

Sensors and Perception
Data Processing / Fusion Methodologies, etc.

Verification and Validation
Methodologies & Application Experiences, etc.

Self-Driving Cars

Diverse human-machine interaction

Structured environment

GPS & map-based navigation

Distributed and cloud-based autonomy

Cyber-security for consumer product

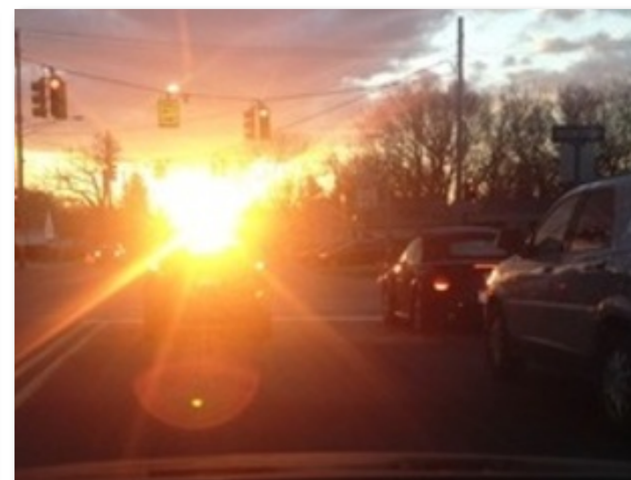
…

Imperfect vehicle autonomy

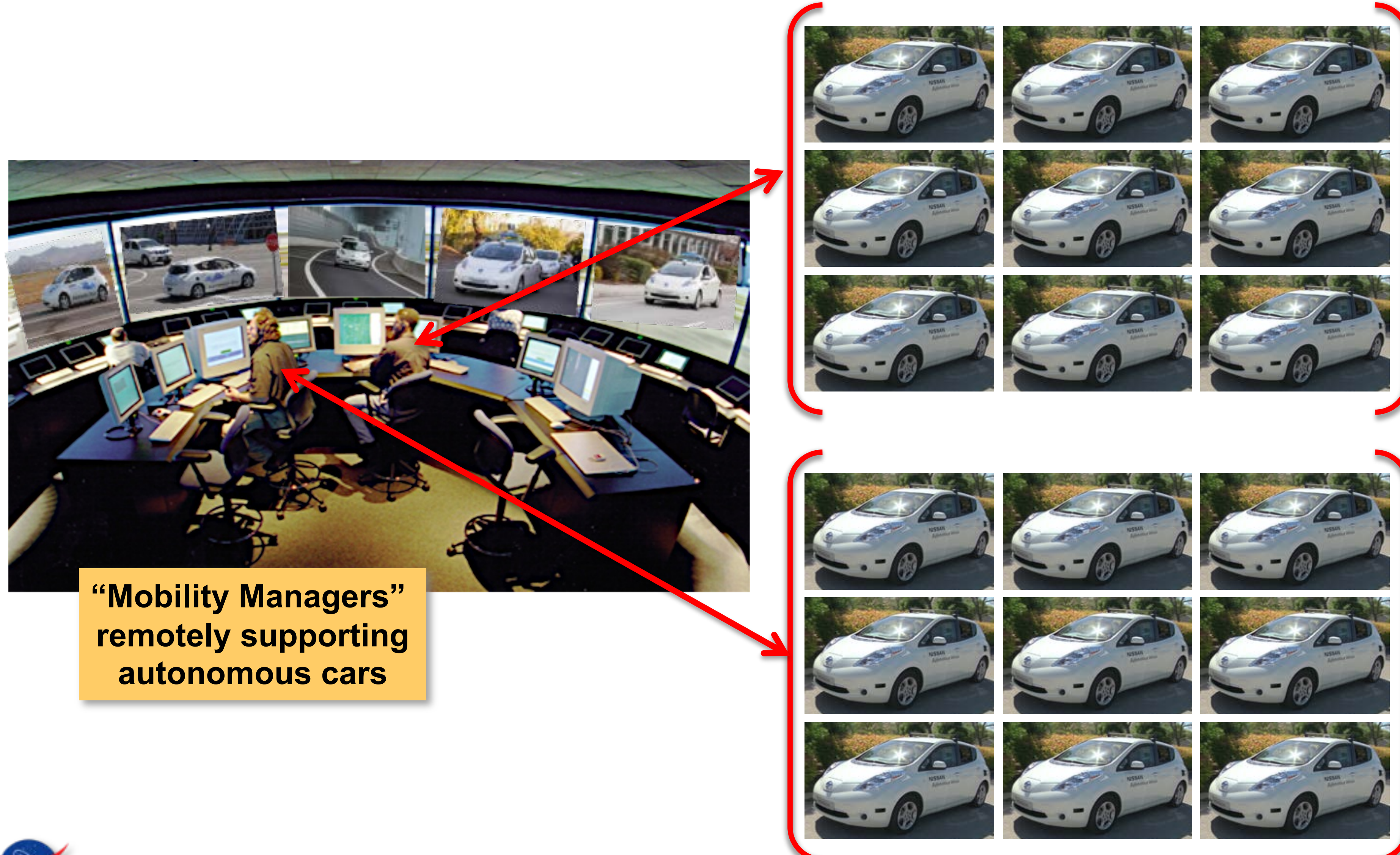
Edge cases, corner cases, and anomalies

- When a construction worker uses hand gestures to provide guidance, or direction, no autonomous car today can reliably make the right decision.
- When the sun is immediately behind a traffic light, most cameras will not be able to recognize the color of the signal through the glare.
- If we see children distracted by the ice cream truck across the street, we know to slow down, as they may dash toward it.

– Andrew Ng (Wired, 3/15/2016)

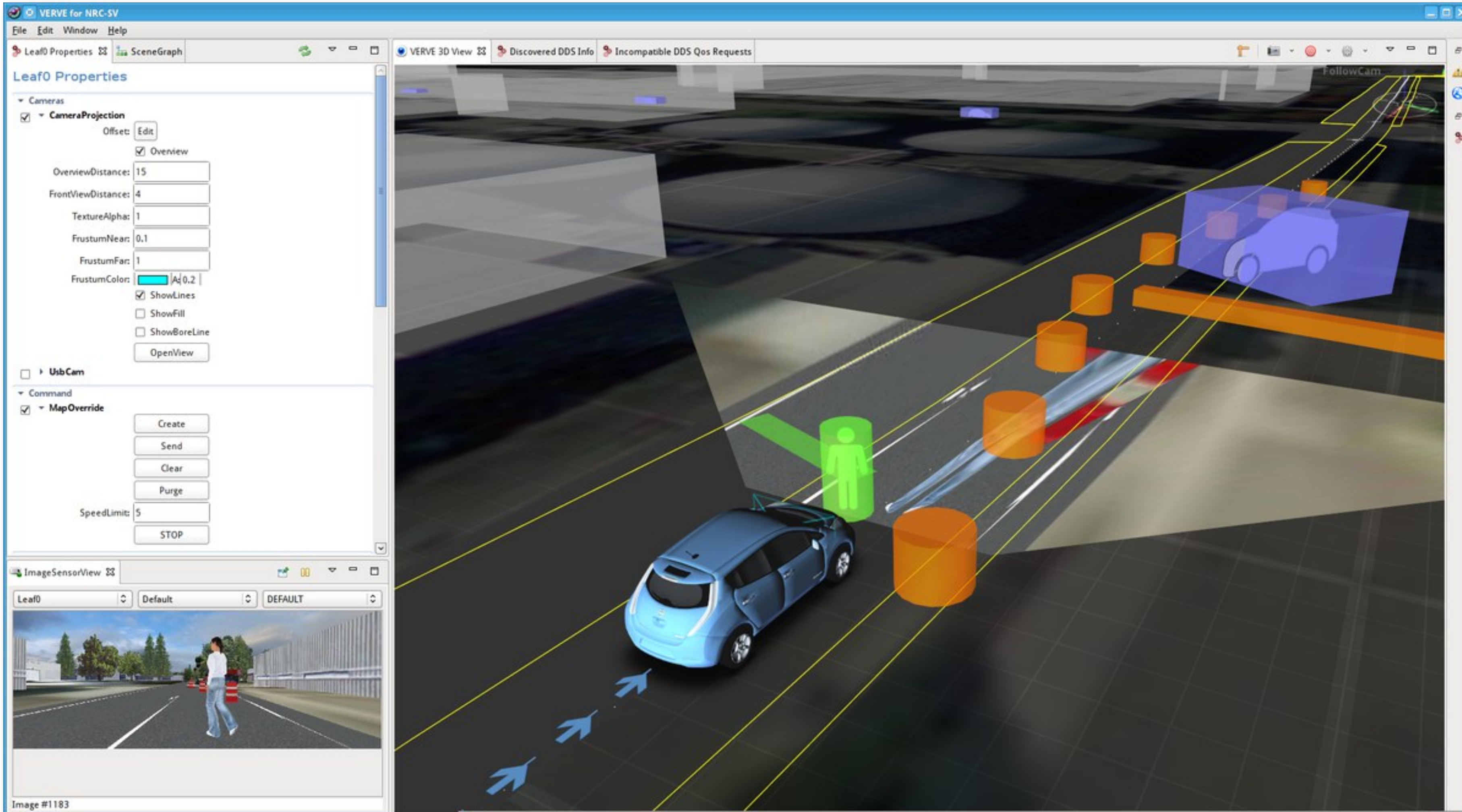


Support center for self-driving cars



Images courtesy Nissan North America

Vehicle assist: Situation assessment



Vehicle assist: High-level guidance

CES 2017 Demo

Human remotely helping a self-driving car

January 6, 2017
Consumer Electronics Show (Las Vegas) & NASA Ames

Working with NASA: Partnerships

Academic

- The Robotics Institute
- Leland Stanford Junior University
- Vanderbilt University
- MIT
- Case Western Reserve University, Est. 1826
- Berkeley, University of California
- Rutgers, The State University of New Jersey
- University of Idaho
- USC
- Brigham Young University (BYU), Provo, Utah
- Wisconsin, University of Wisconsin–Madison
- Cornell University
- Universiteit Gent
- SETI Institute
- KAIST, Korea Advanced Institute of Science and Technology, 한국과학기술원

Commercial

- Google
- Nissan
- Astrobotic
- SSL
- Energid, Robotics and Machine Vision
- Otherlab
- Altius Space Machines
- ProtoInnovations
- TRACLabs

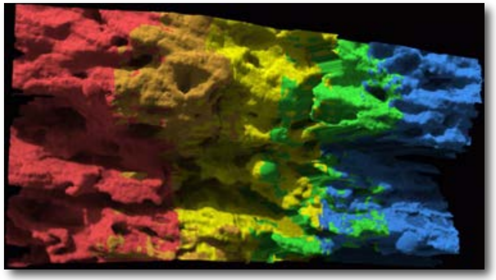
Government

- DARPA
- Marine Corps Warfighting Lab, "Semper Fidelis"
- SPAWAR
- NPS, Praestantia per Scientiam, 1909
- Naval Research Laboratory, Washington, DC
- USGS, science for a changing world

Working with NASA: Software Licensing

Vision Workbench

Apache 2

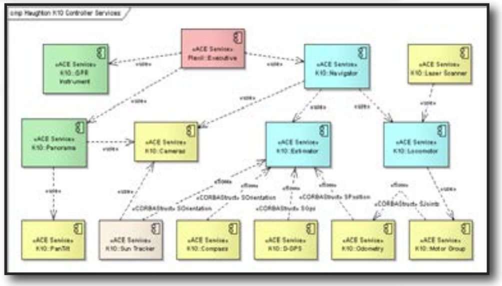


Exploration Ground Data Sys. (xGDS)

Apache 2

RoverSW

NOSA 1.3



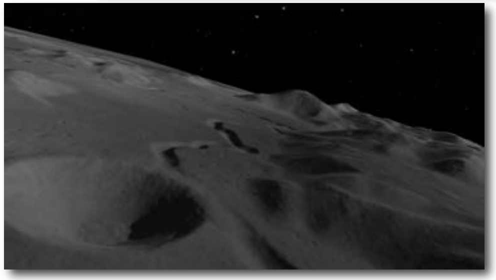
Visual Environment for Remote Virtual Exploration (VERVE)

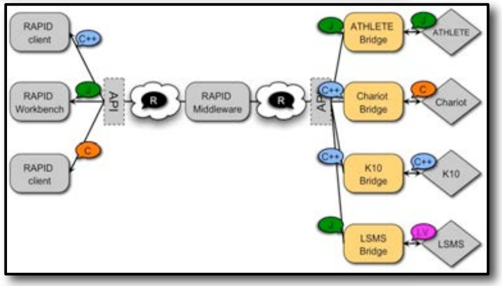
Apache 2

Neo Geography Toolkit

(Ames Stereo Pipeline)

Apache 2



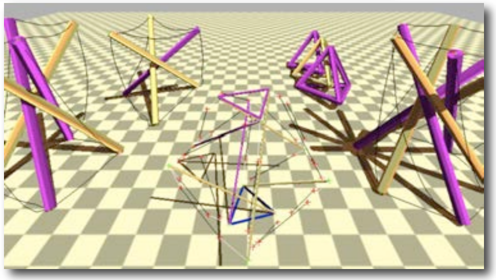


RAPID (NASA robot middleware)

Apache 2

NASA Tensegrity Robotics Toolkit

Apache 2



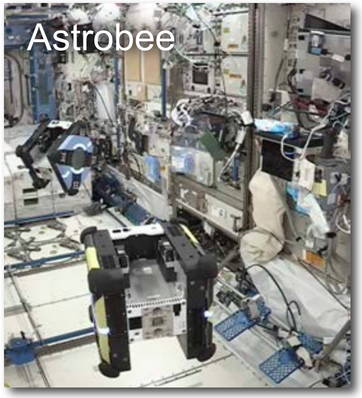
Astrobee Robot Software

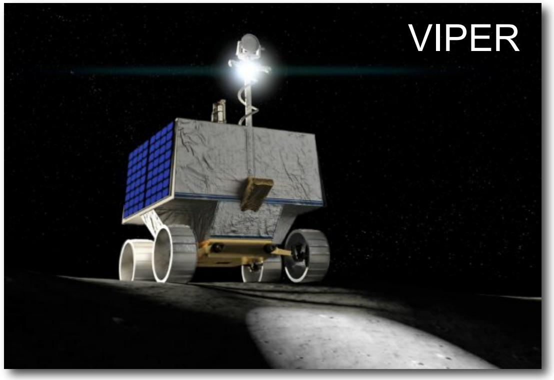
Apache 2

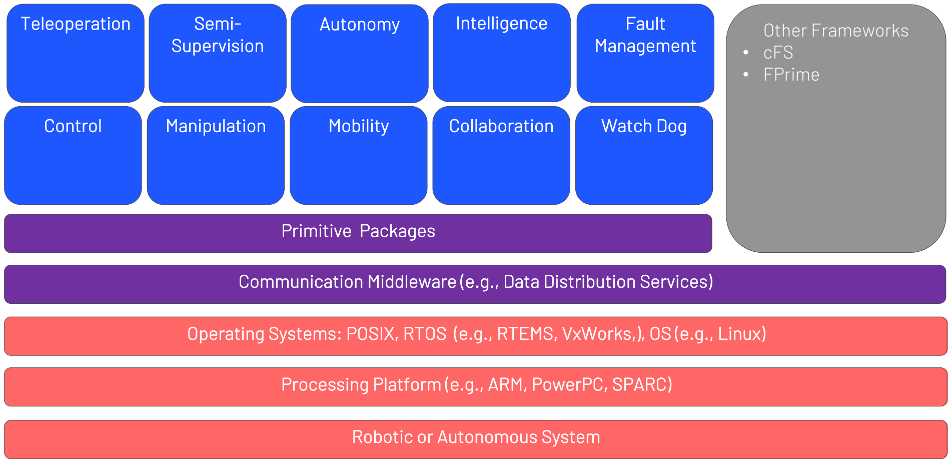
Working with NASA: Space ROS

Robot Operating System 2 (ROS) for Space

- **Adapt** and **mature** terrestrial robotics software technology for space use
- **Space qualify** portions of ROS 2 (follow NASA mission practice)
- Create a **registry** to facilitate reuse (inspired by "ROS-M" approach)







Ames (ARC)
Goddard (GSFC)
Johnson (JSC)

BLUE ORIGIN

open robotics

Questions?

Intelligent Robotics Group

Intelligent Systems Division

NASA Ames Research Center

irg.arc.nasa.gov