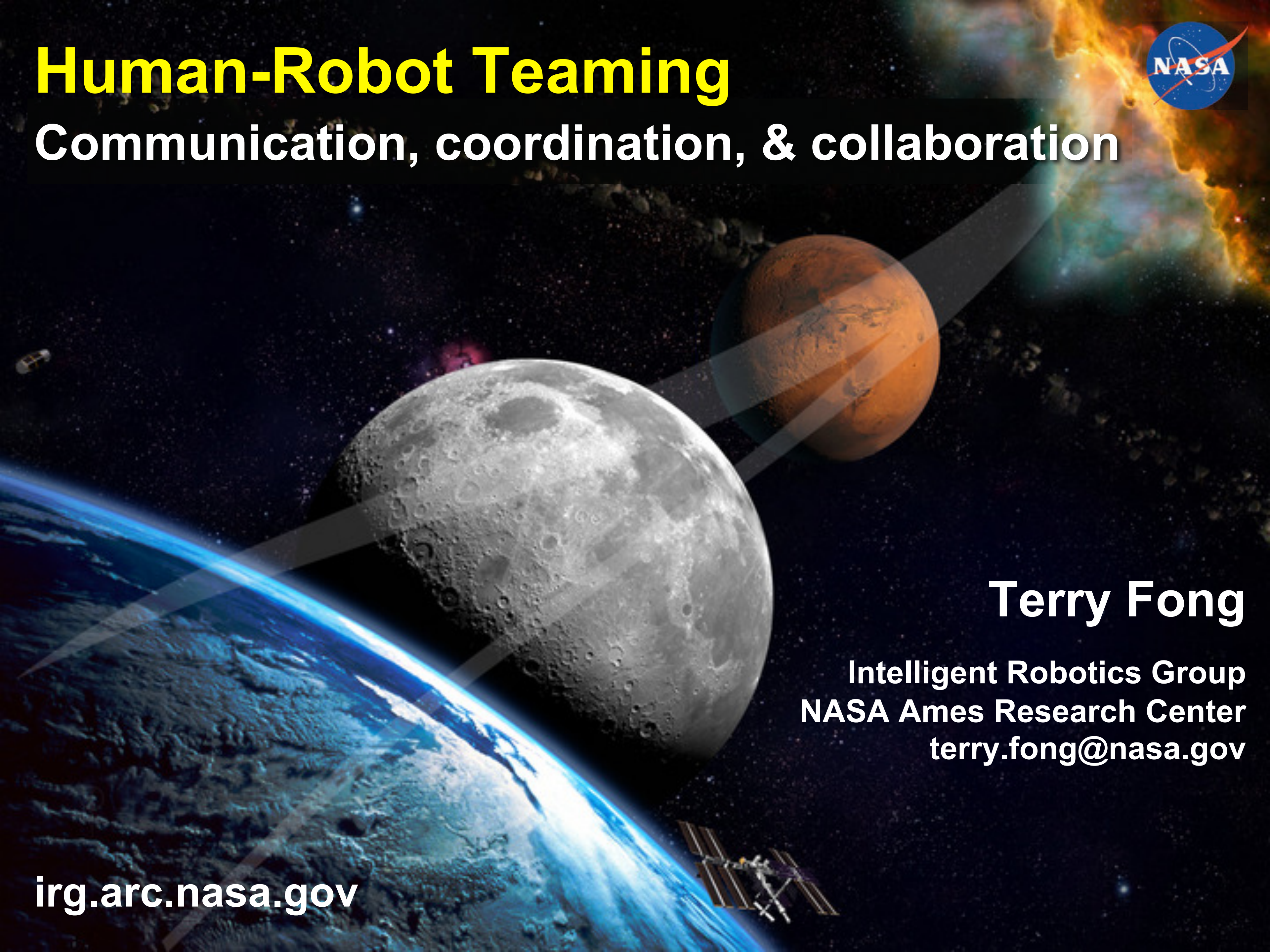
Human-Robot Teaming

Communication, coordination, & collaboration



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What is a team?

"A group of people who work together"
– Merriam-Webster

Teams are interdependent

- Members share a common goal
- Group needs outweigh individuals
- Must have common ground & trust

Norms (governing behaviors)

- Background (experience, training, knowledge, culture, etc.)
- Org structure (chain of command)
- Work protocol (doctrine)

Cornerstones of teamwork

- Communication
- Coordination
- Collaboration

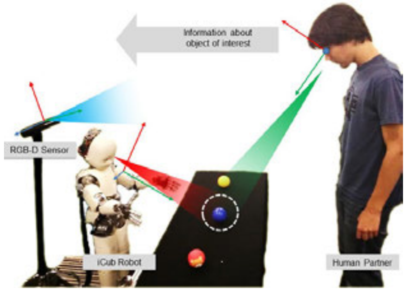
Communication

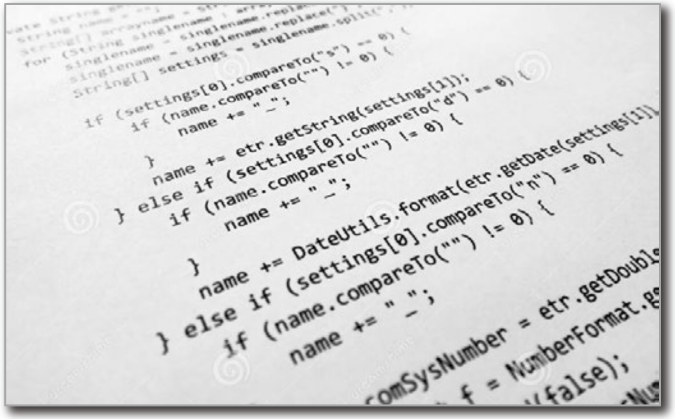
Signals

- Limited content (few bits)
- Convey awareness, intent, state, etc.
- Numerous mechanisms
(combine for emphasis & redundancy)
    - Auditory
    - Gaze
    - Gesture
    - Motion

Language

- Extensive content (many bits)
- Convey high level of detail
- Specific vs. general
    - Task specific
    - Domain specific
    - Natural





```
String[] settings = singlename.split(
if (settings[0].compareTo("s") == 0) {
    if (name.compareTo("") != 0) {
        name += "_";
    }
    name += etr.getString(settings[1]);
} else if (settings[0].compareTo("d") == 0) {
    if (name.compareTo("") != 0) {
        name += "_";
    }
    name += DateUtils.format(etr.getDate(settings[1]
} else if (settings[0].compareTo("n") == 0) {
    if (name.compareTo("") != 0) {
        name += "_";
```

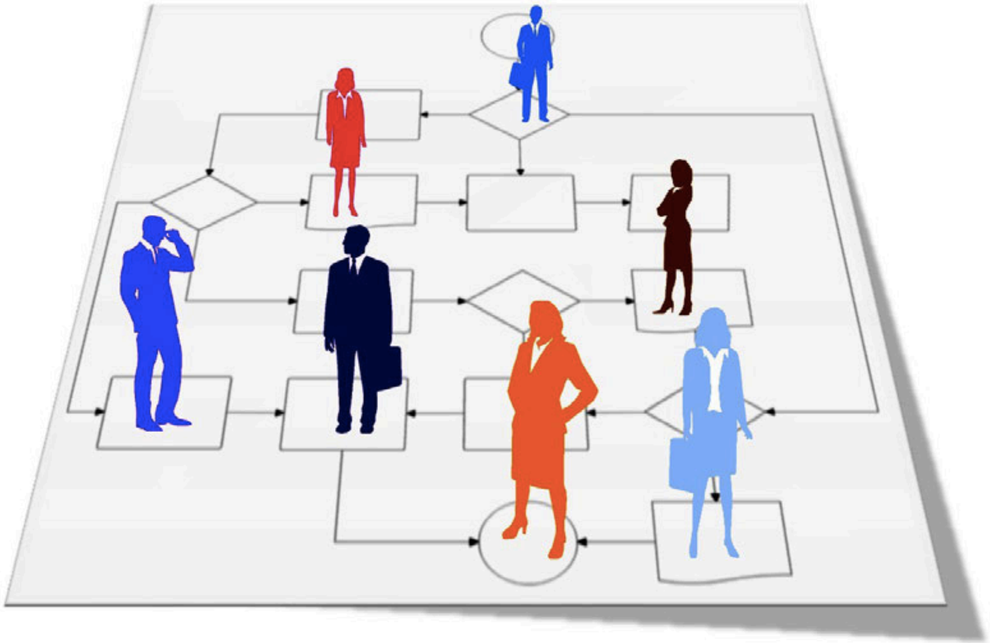
Coordination

“Harmonious functioning”

- Making sure that two or more people (or groups of people) can work together properly and well
- Involves integration of activities, responsibilities, etc. to ensure that resources are used efficiently and effectively
- Requires control, organization, monitoring, etc.

Effective coordination requires:

- **Common ground**: mutual knowledge that supports joint activity
- **Directability**: assessing and modifying individual actions within joint activity
- **Interpredictability**: being able to predict what others will do



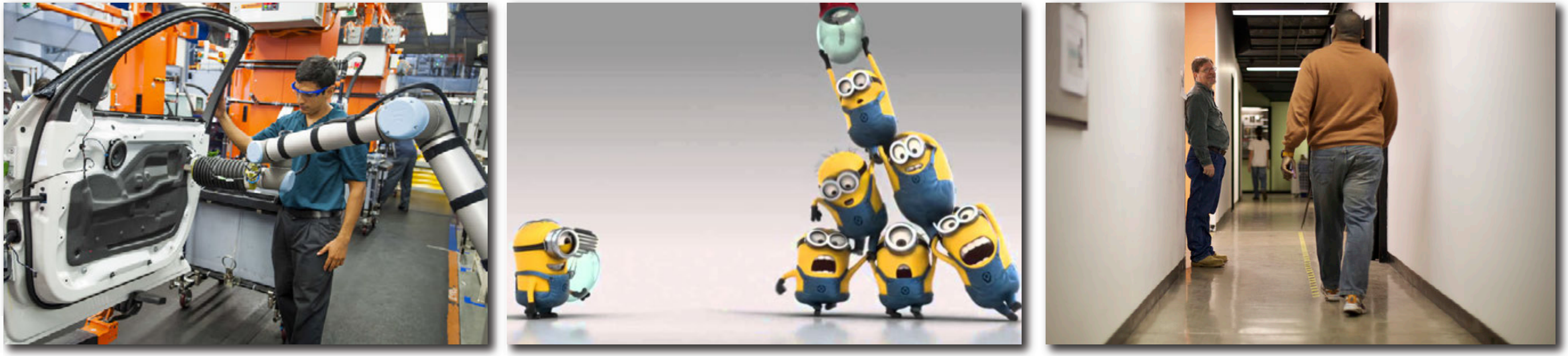
Collaboration

Joint work

- Multiple individuals working together to achieve a shared objective
- Requires communication and coordination
- Involves sharing of knowledge, intention, and goals

Collaborative tasks

- **Tightly coupled**: each participant depends on the actions of other individuals (jointly pushing a sofa)
- **Loosely coupled**: each participant engages in complementary actions towards a shared goal (splitting up to search)
- **Planned** vs. **spontaneous**: depends on environment, situation, task, etc.



Can robots be (good) teammates?

Assumptions

- Robots **should be** team members
- Robots can be **successful** and **trusted** team members
- Human teams are a **good model** for human-robot teams

Robots have (engineered) limits

- Robots often cannot handle **anomalies**, **edge cases**, & **corner cases**
- Appearance can be deceiving: **a humanoid robot ≠ a human**

Humans have difficulty creating mental models of robots

- Hard to set and manage **expectations** of robot behavior & performance
- Teamwork may be unnatural and inefficient (high human workload)

Robots have difficulty recognizing human intent

- Robot **may not act** at the right time or respond properly
- Teamwork may be slow and jittery

Human-robot teams (for space)

Many forms of human-robot teaming

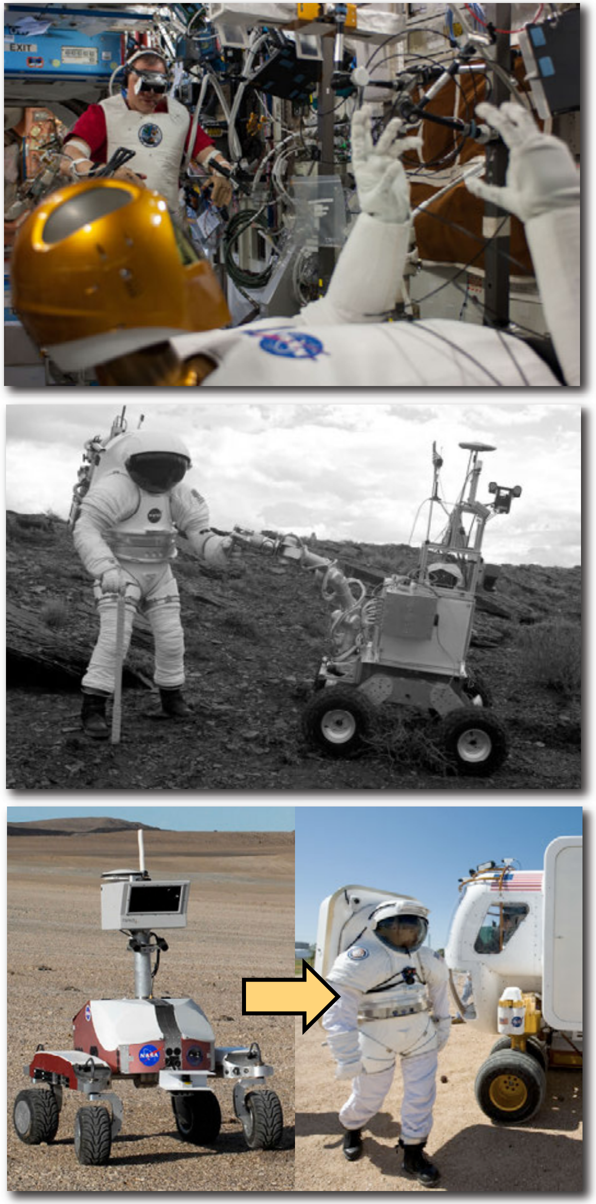
- “Robot as tool” is only **one** model
- Not just co-located or line-of-sight
- ▸ **Peer-to-peer teaming is also important**

Concurrent, interdependent operations

- Human-robot interaction is still **slow** and **mismatched** (compared to human teams)
- Easy for robots to impede the human
- ▸ **Loosely-coupled teaming is essential**

Distributed teams

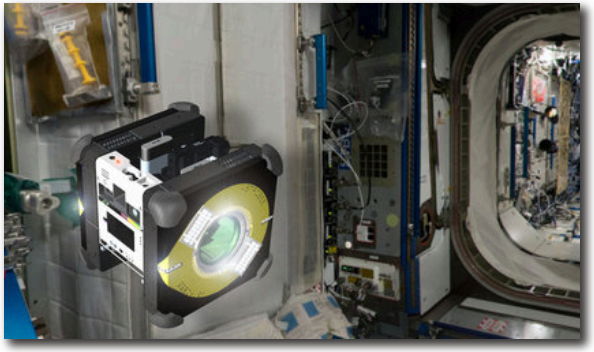
- Require **coordination** and **info exchange**
- Require understanding of (and planning for) each teammate’s **capabilities**
- ▸ **Effective protocols and tools are critical**



Research @ NASA Ames

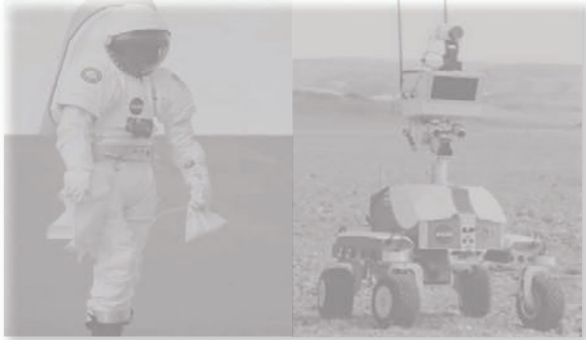
Part 1: Communication

- Signaling for non-humanoid robots
- Convey robot state and intent using dynamic light and sound
- Ambient and active communication



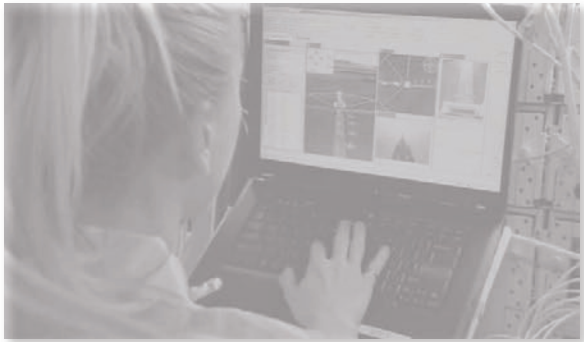
Part 2: Coordination

- Achieve common (joint) objective
- Independent human and robot activities
- Robots work before, in parallel (loosely coupled) and after humans



Part 3: Collaboration

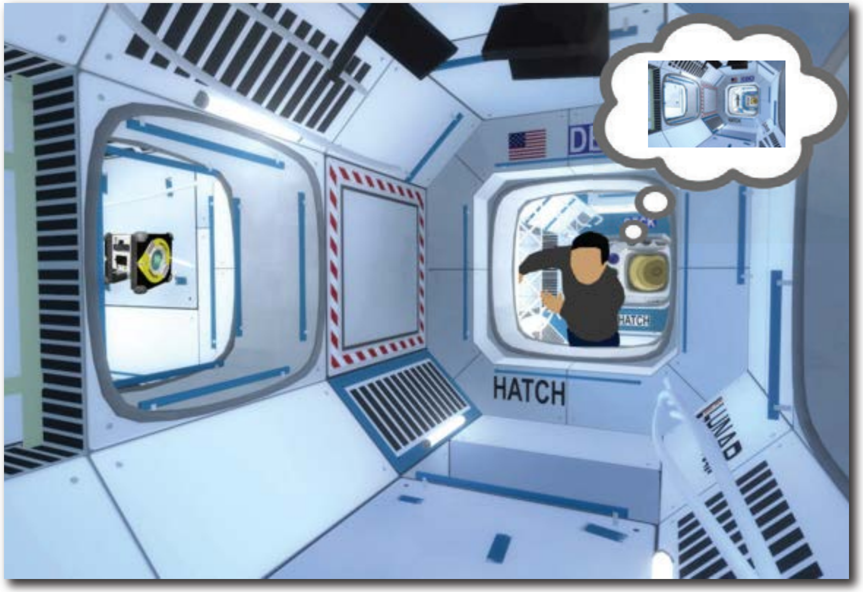
- Humans support autonomous robots
- Focus on cognitive tasks (planning, decision making, etc)
- Human-robot team may be distributed

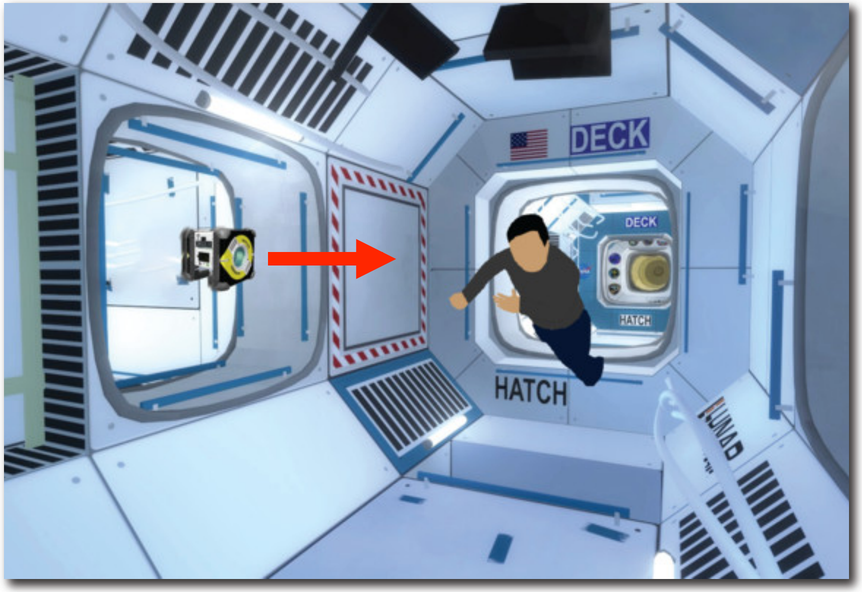


Motivation

Situation awareness

- Robot is positioned out of the human's view
- Signals can indicate the presence and location of the robot to facilitate SA (at multiple levels)
- Signals can facilitate prediction and planning (avoid conflict before it occurs, avoid dangerous situation, etc).

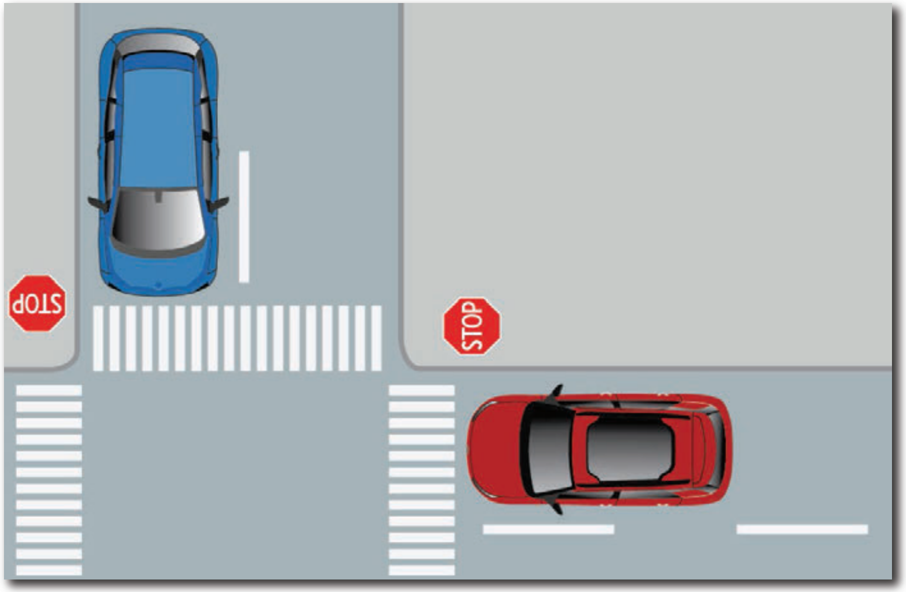


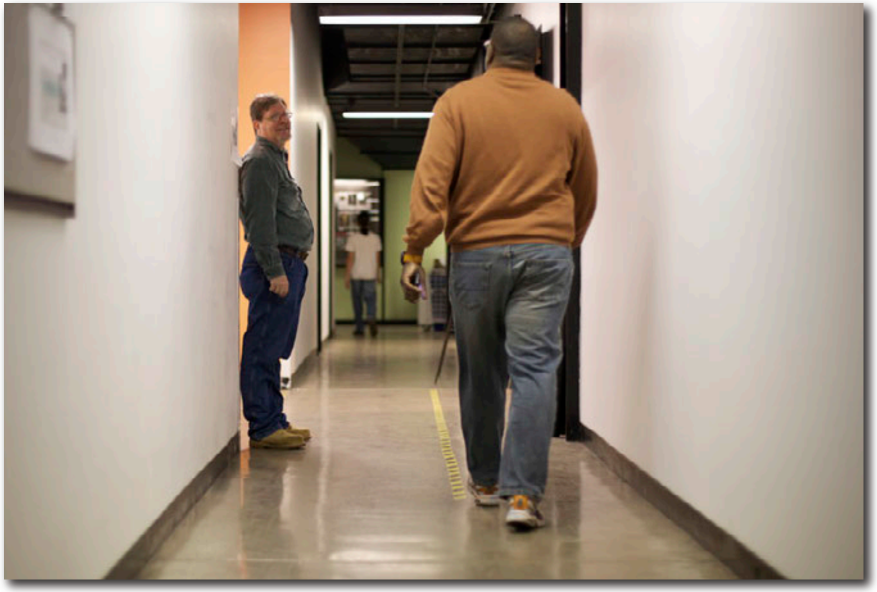


Motivation

Spatial negotiation

- When humans and robots must co-exist in the same space, there is often a need for spatial negotiation
- Cannot always rely on pre-defined rules (e.g., “right of way”) due to ambiguity and uncertainty
- Signaling (lights, movement, sound, etc) is an effective manner to communicate intent and elicit action.

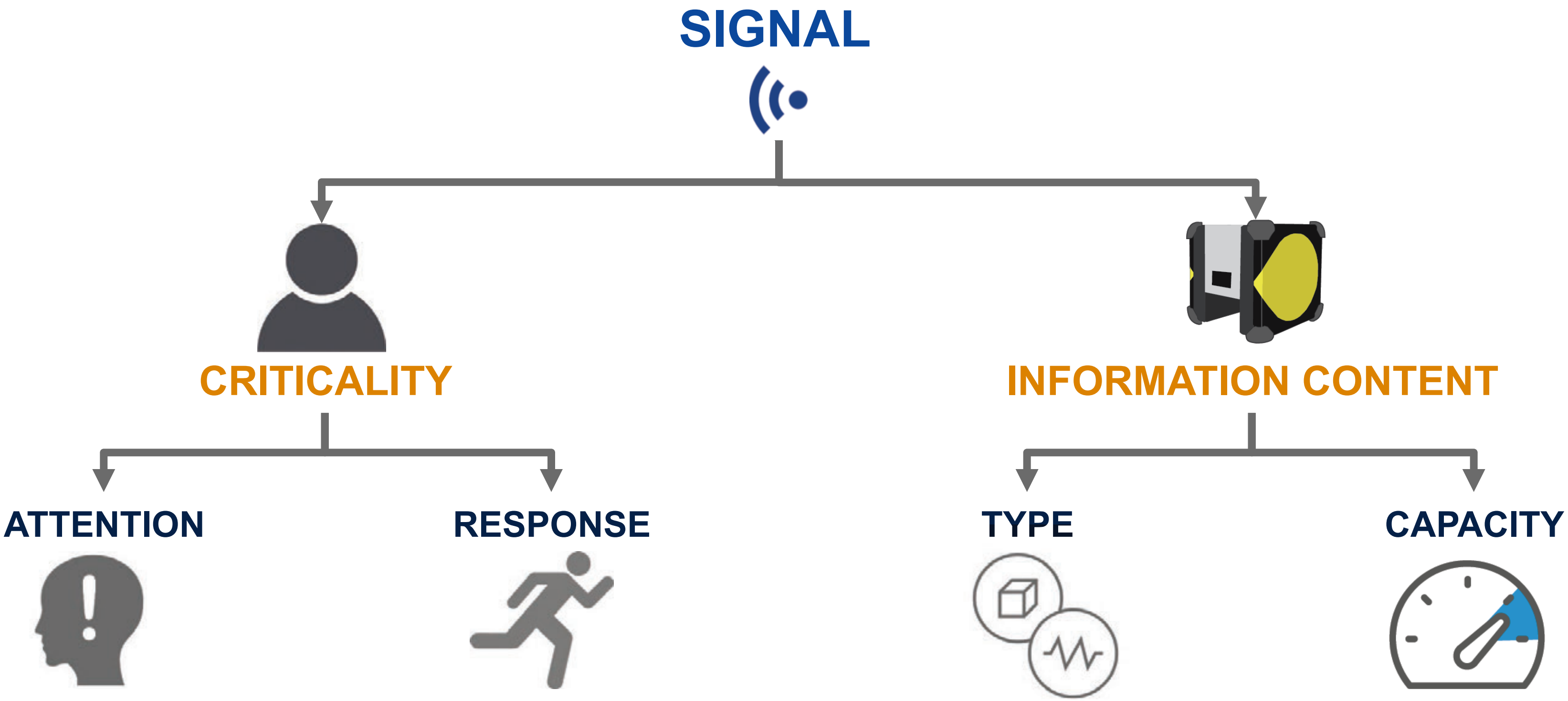




Using signals

Considerations

- **What** to convey (importance of the information)
- **When** to convey (timing of the information)
- **How** to convey (constrained/modulated by configuration, situation, etc..)
- **To whom** do we convey (user role, capability to receive/respond, etc.)



SIGNAL

CRITICALITY

INFORMATION CONTENT

ATTENTION

RESPONSE

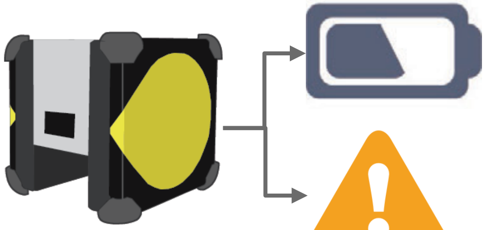
TYPE

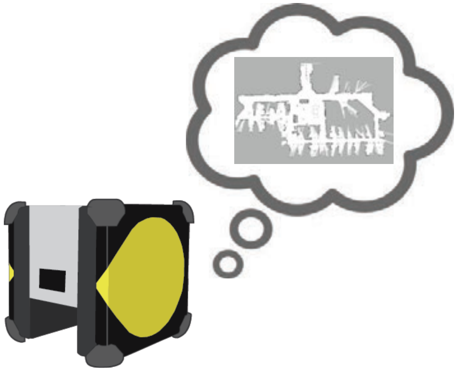
CAPACITY

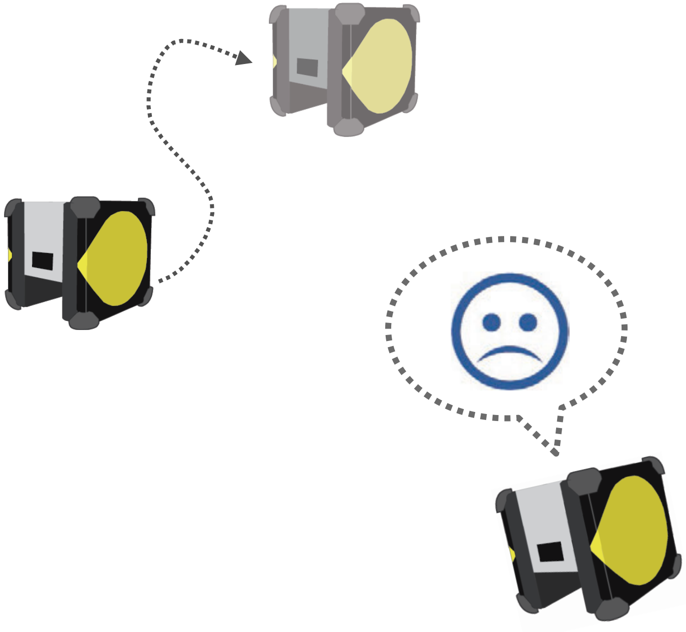
What to convey?

Robot states

- **Condition**
  - Operational status: health, control mode, faults
- **Knowledge**
  - Information the robot possesses about itself, the task, and the world
- **Activity**
  - Actions the robot is taking (or attempting) to take – often task related
- **Affect**
  - The “emotional state” of the robot



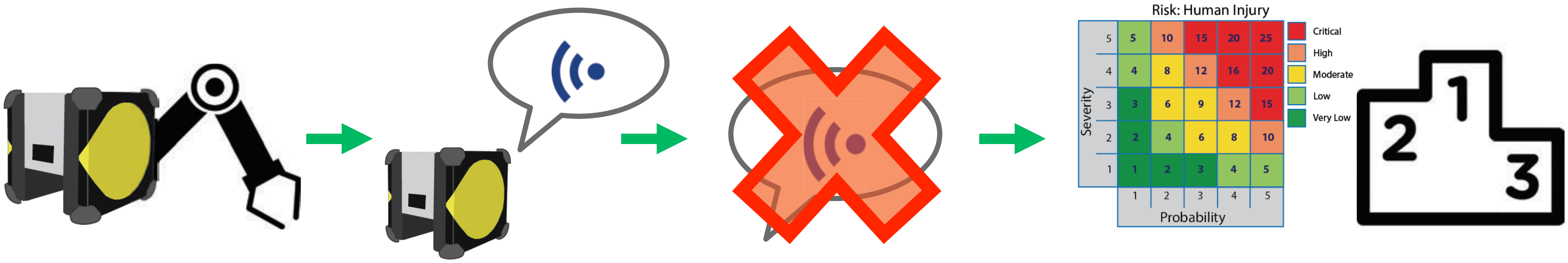




When and how to convey?

Signal design

- **Use Case Analysis**
    - Describe the robot’s goals using use case descriptions
- **Communication Analysis**
    - Describe the robot’s communications within each use case
- **Failure Analysis**
    - Identify the risks of a communication case not occurring
- **Priority Ranking**
    - Weighting different types of risk (e.g., inefficiency vs. human injury)



Risk: Human Injury

Severity					
5	5	10	15	20	25
4	4	8	12	16	20
3	3	6	9	12	15
2	2	4	6	8	10
1	1	2	3	4	5
	1	2	3	4	5
	Probability				

🟥 Critical
🟧 High
🟨 Moderate
🟩 Low
🟩 Very Low

E. Cha, Y. Kim, T. Fong, and M. Mataric (2017) **“A system for designing human-robot communication”** *(in submission)*

Signal notification level

Demand Reaction	**Interrupt until human responds / intervenes**
Interrupt	**Request attention from human**
Make Aware	Help humans decide their further action
Change Blind	Help humans monitor robot's overall action
Ignore	Optional (non-critical) information

Signaling for non-humanoid robots

Considerations

- **Embodiment**
  - Form: How does the robot's physical form affect signaling capabilities?
  - Generalizability: How can the same signals be utilized across platforms?
- **Signal design**
  - Intuitiveness: How to utilize non-humanoid communication modalities to signal in an intuitive manner?
  - Complexity: How to create signals of varying complexity utilizing non-humanoid communication modalities?
- **External factors**
  - Environment: How to account for the environment (e.g., perceptual conditions, ambient noise) and external events in signaling?
- **Psychological factors**
  - Perception: How to control humans' perceptions of the robot's signals?
  - Evaluation: How to accurately evaluate signals in real world scenarios?

E. Cha, Y. Kim, T. Fong, and M. Mataric (2017) **"A survey of non-verbal signaling methods for non-humanoid robots"** *(in submission)*

Astrobee free-flying space robot

Specs

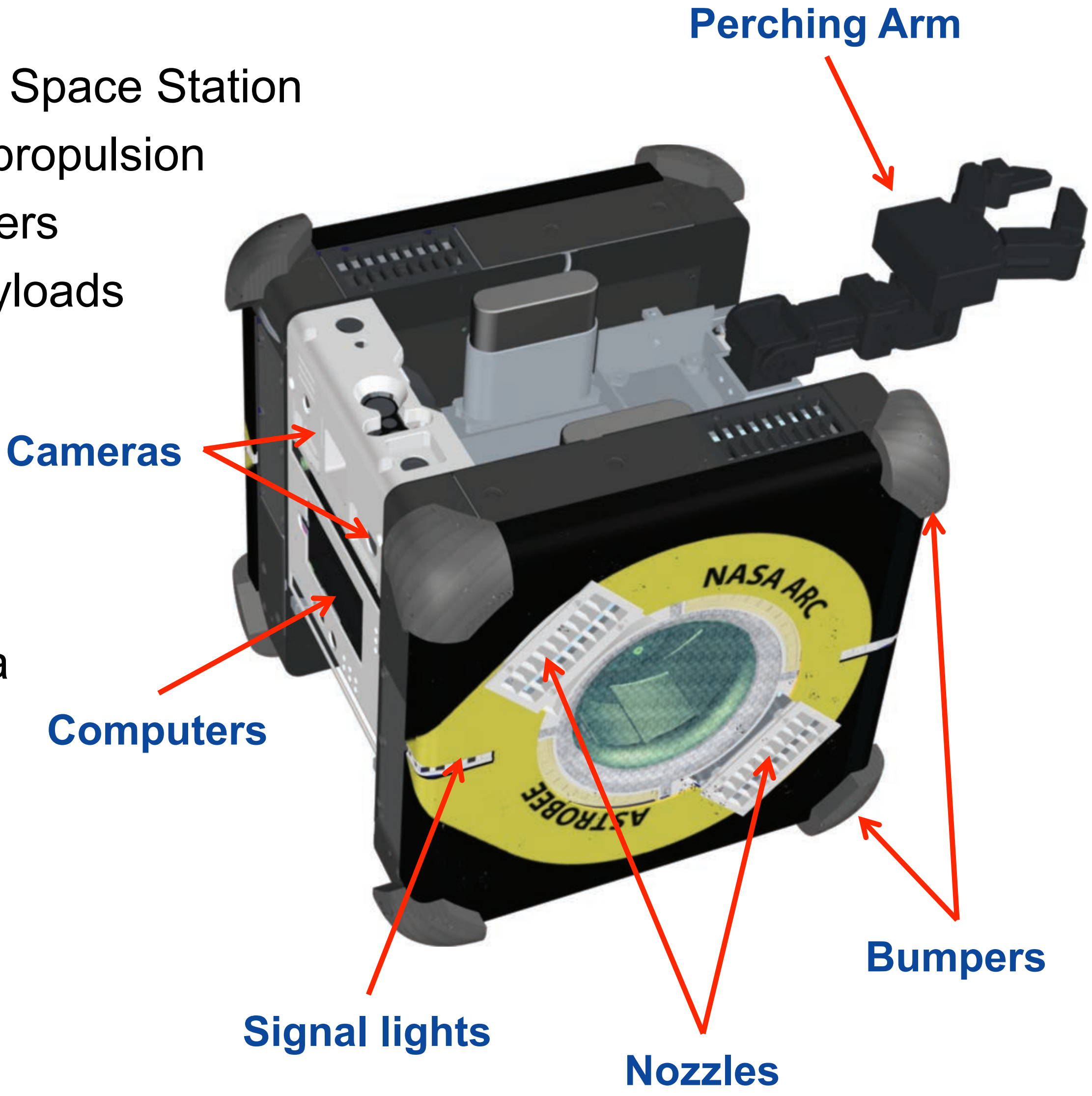
- Free flying robot inside the Space Station
- All electric with fan-based propulsion
- Three smartphone computers
- Expansion port for new payloads
- Open-source software
- 30x30x30 cm, 8 kg

Uses

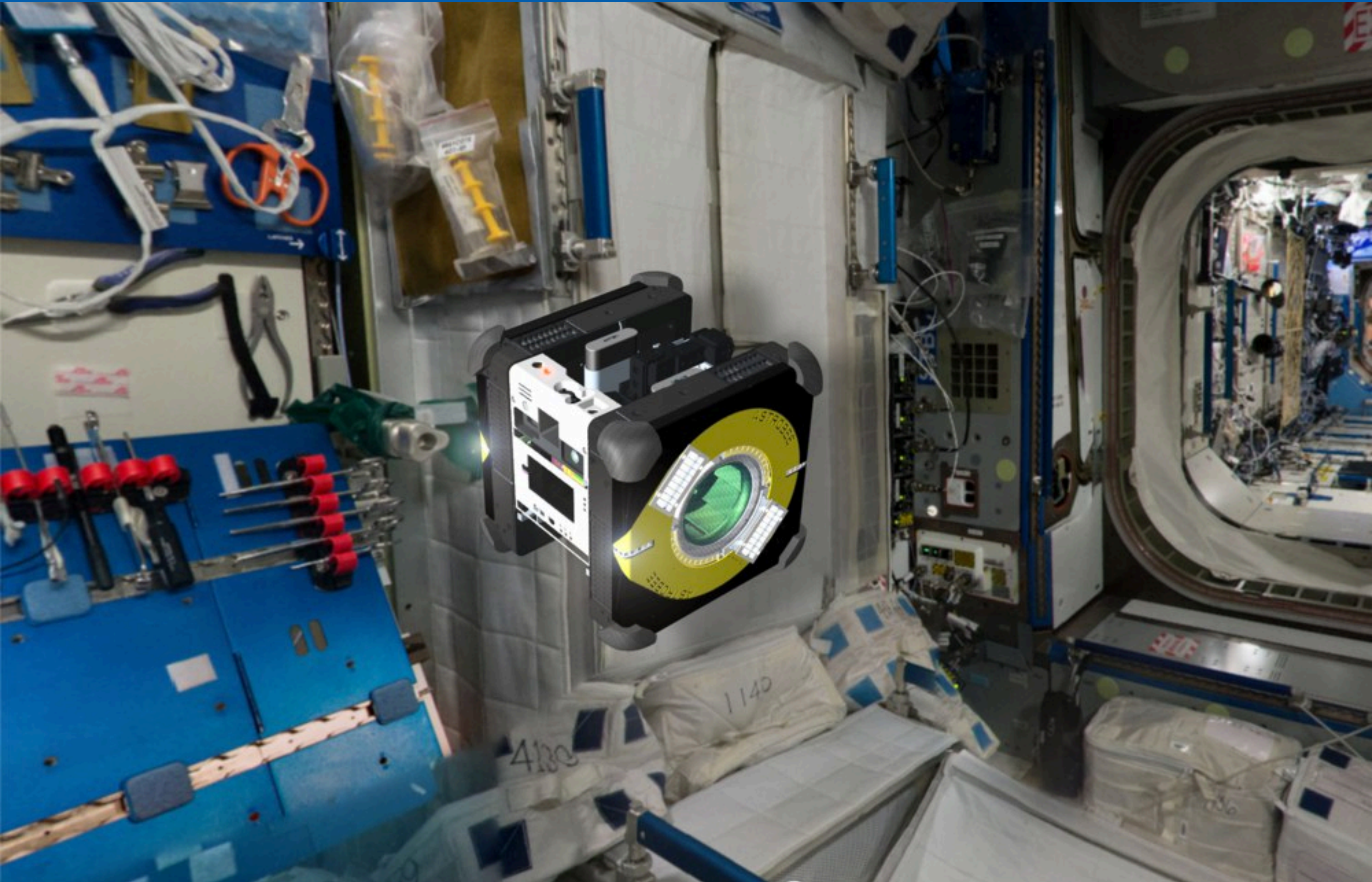
- Mobile sensor
- Remotely operated camera
- Zero-G robotic research

Autonomy

- Docking & recharge
- Perching on handrails
- Vision-based navigation



Astrobee on the Space Station (concept)



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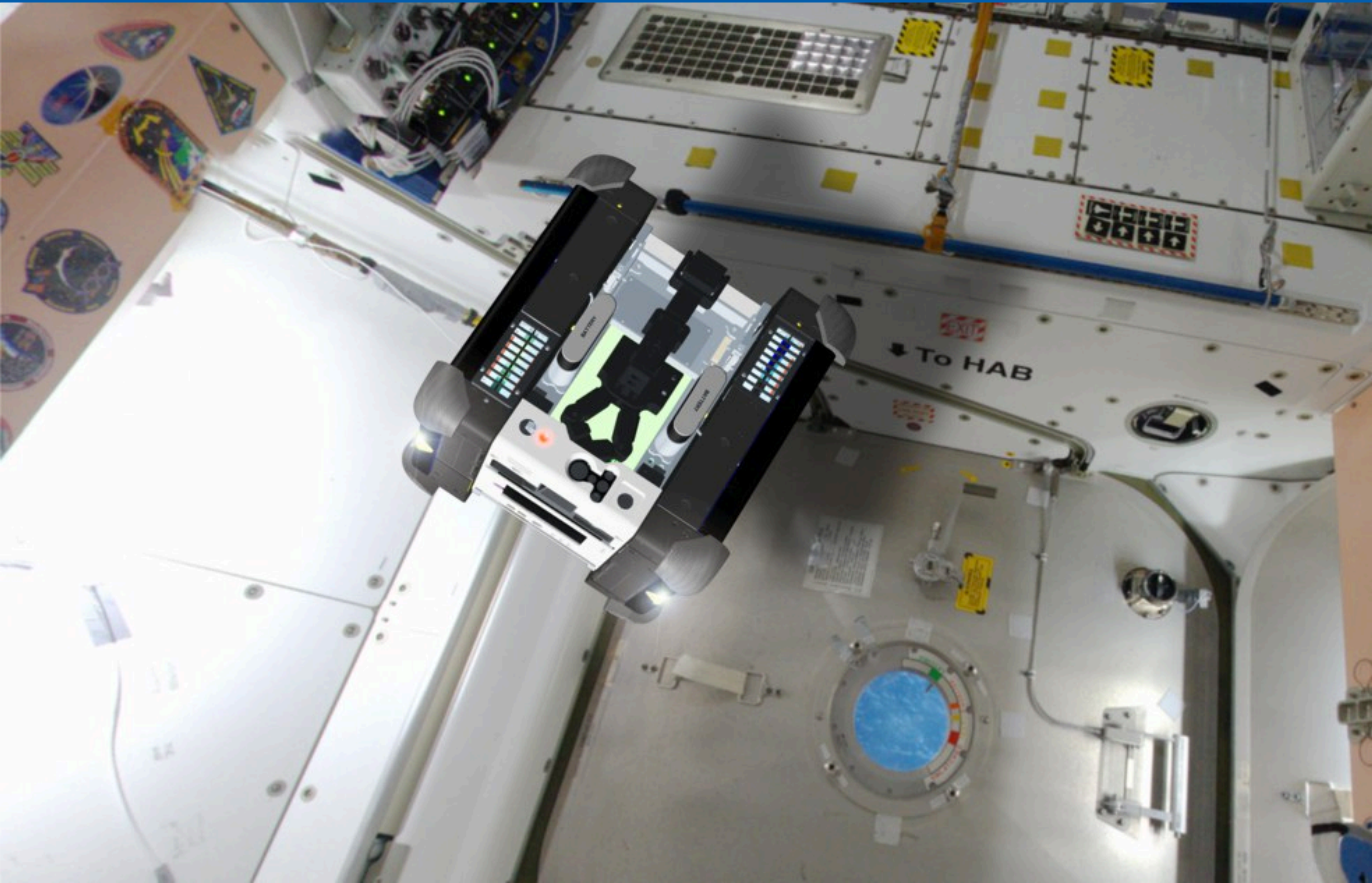
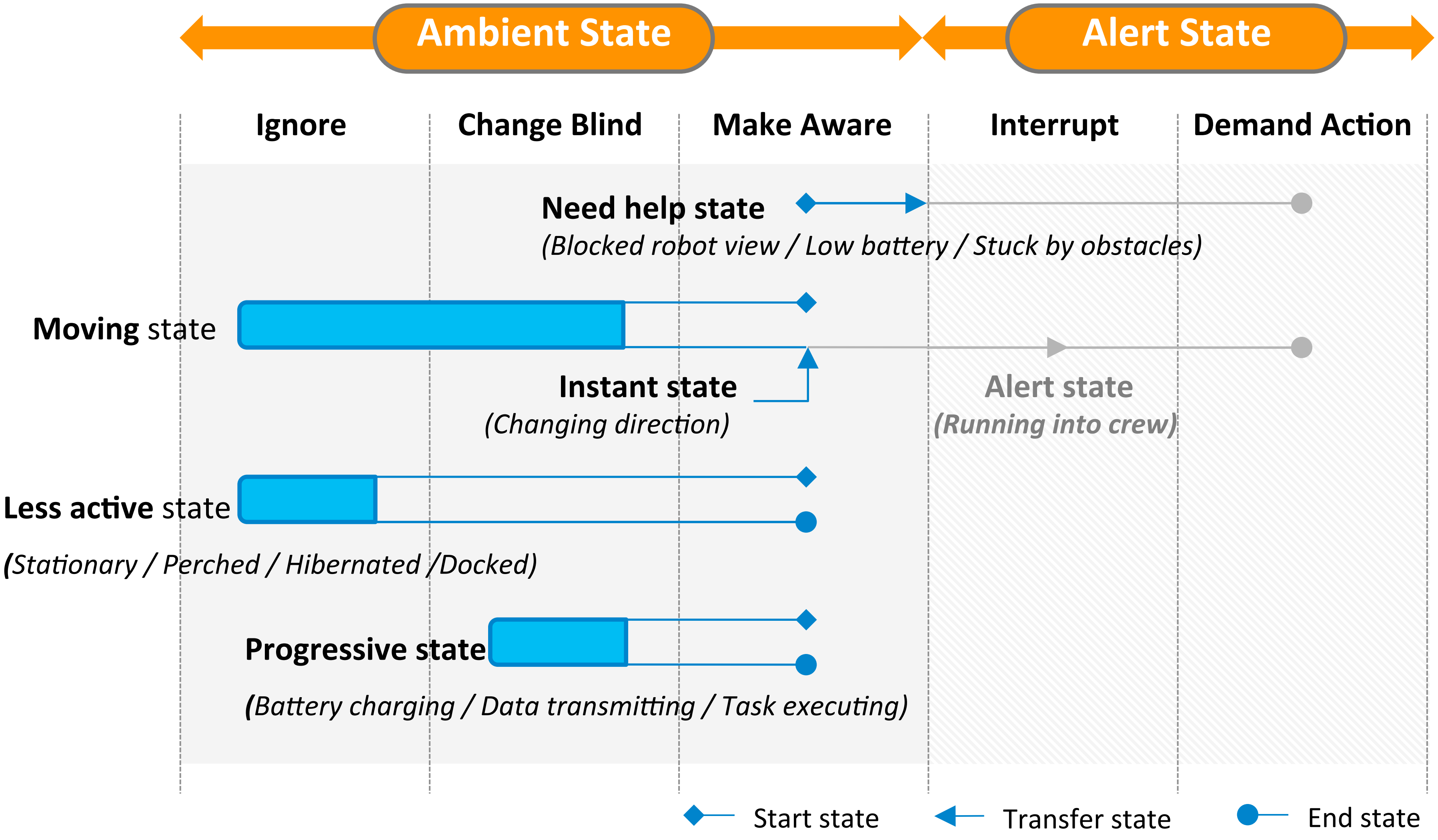


Astrobee on the Space Station (concept)

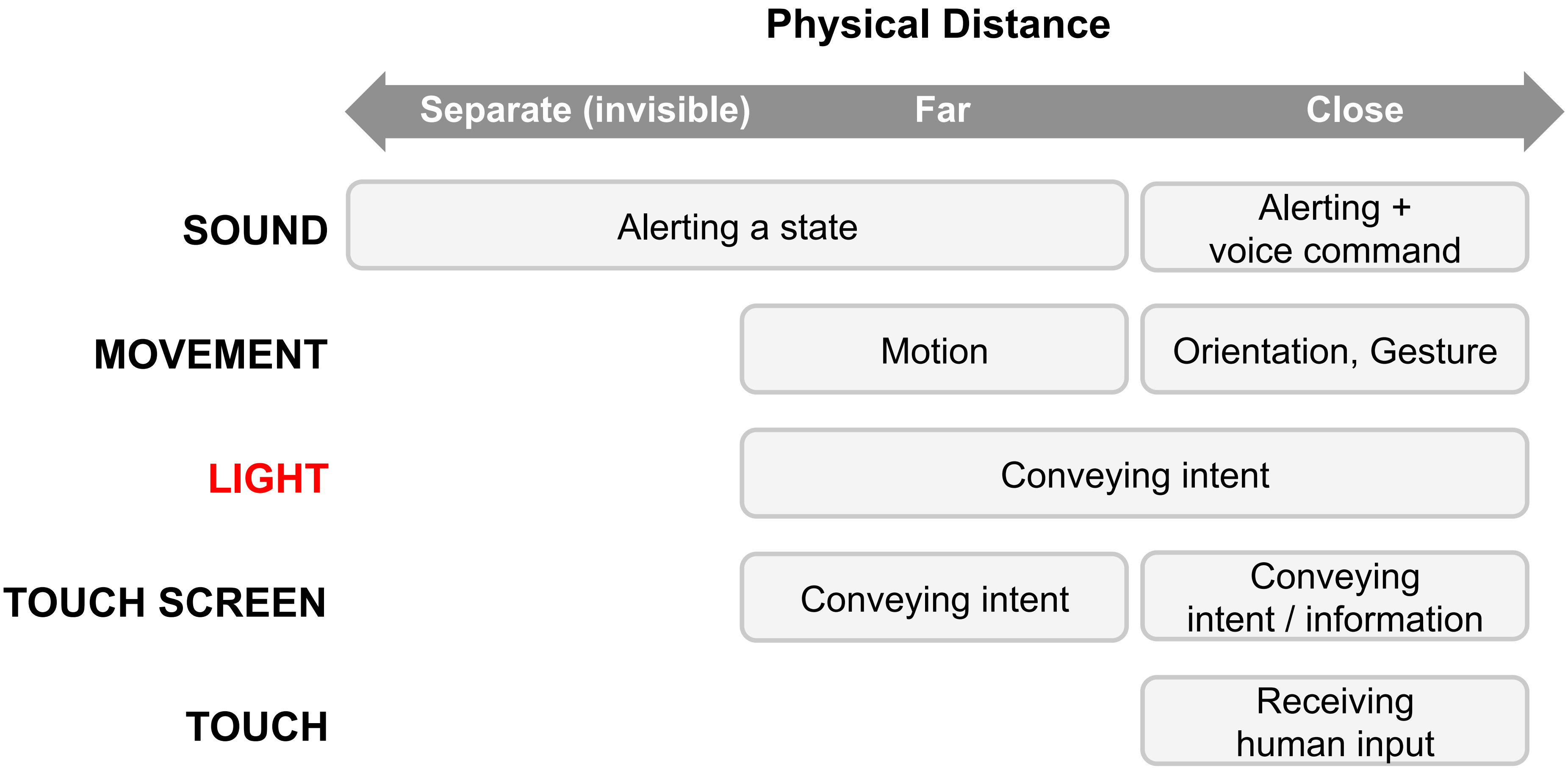
Astrobee states

Situation	States						
On/Off	On/Off state						
Perching	Perching progress	Camera streaming mode	pointing where to move - heading (handle)				
Error	Low power	Stuck					
Work	Action or task	Goal (research plan / camera mode / search mode)	Progress (doing/ completing / awaiting further order)	Priority / urgency	Assistance required for task or fault recovery		
Motion	Moving direction to warn	Destination	Speed or accel.	Purpose	Trajectory	Coming into view	Adjacency (to human or obstacle)

Notification levels



Possible signals



Physical Distance

Separate (invisible)
Far
Close

SOUND
Alerting a state
Alerting + voice command

MOVEMENT
Motion
Orientation, Gesture

LIGHT
Conveying intent

TOUCH SCREEN
Conveying intent
Conveying intent / information

TOUCH
Receiving human input

Light signaling for free-flying robots


beacon

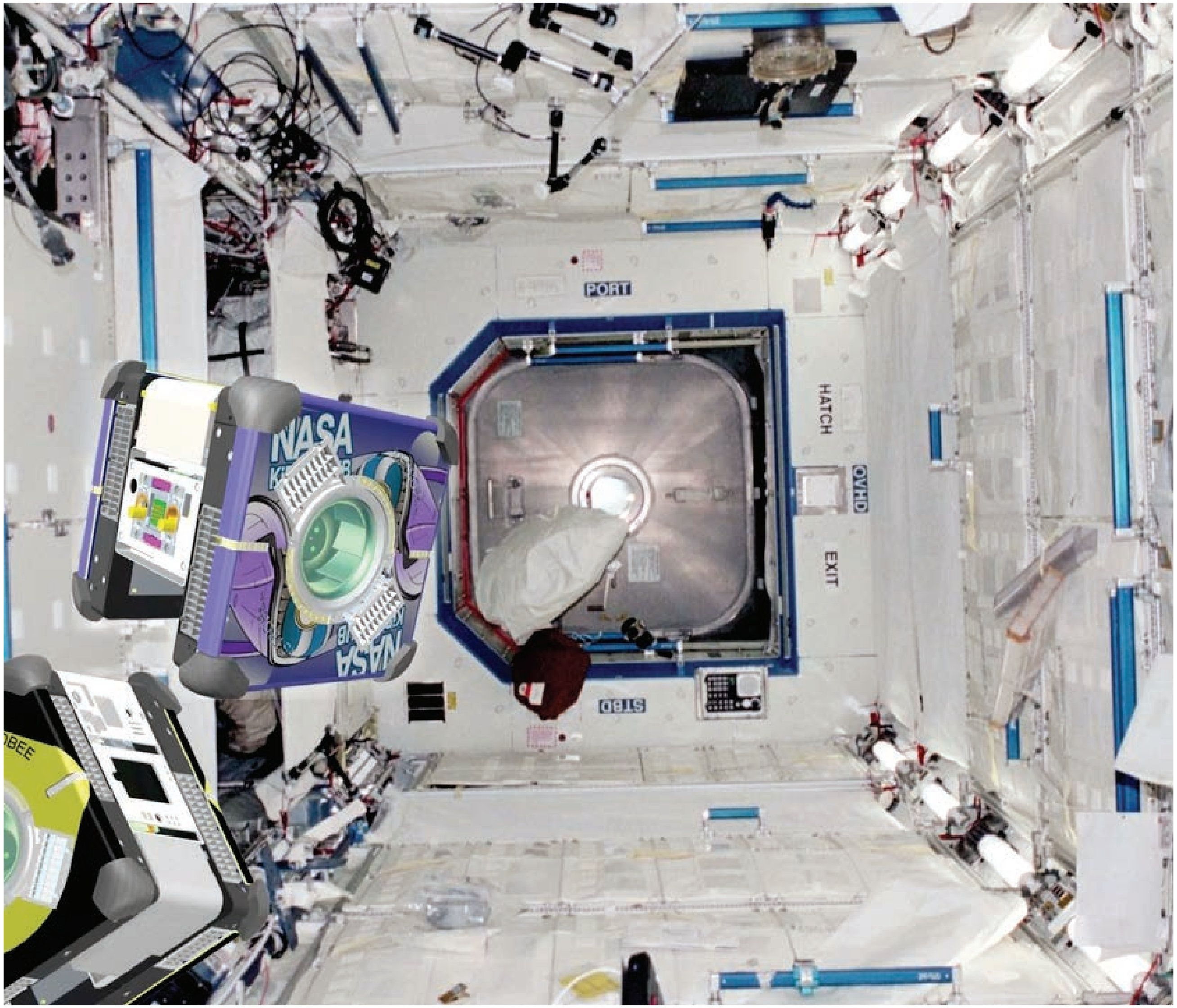

blinker


gaze


thruster

D. Szafir, B. Mutlu, and T. Fong (2015) **“Communicating directionality in flying robots”.** ACM/IEEE HRI Conf.

Astrobee light signal concept



Research @ NASA Ames

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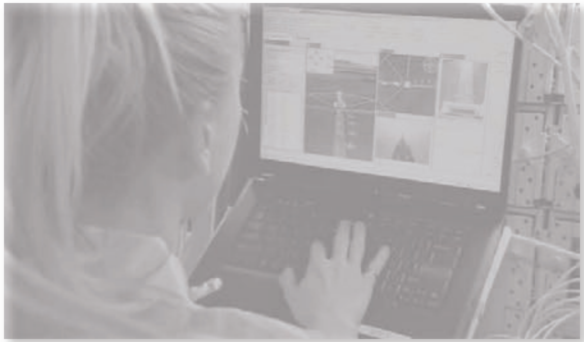
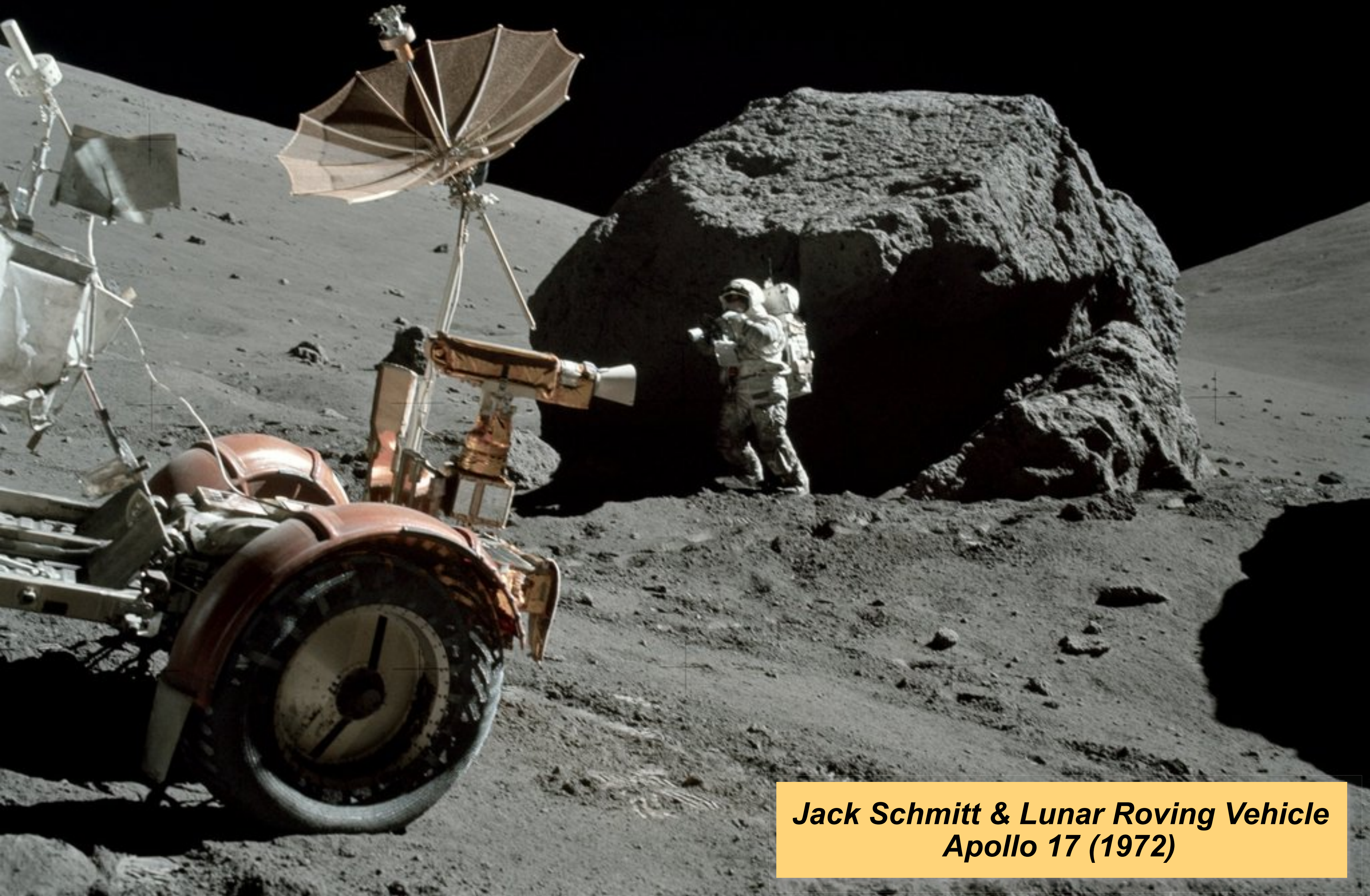
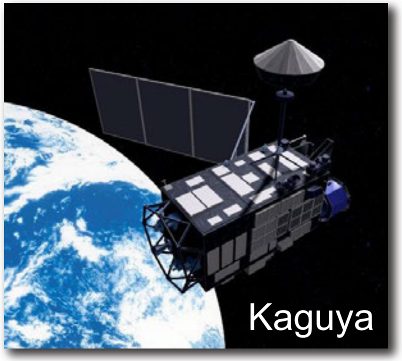


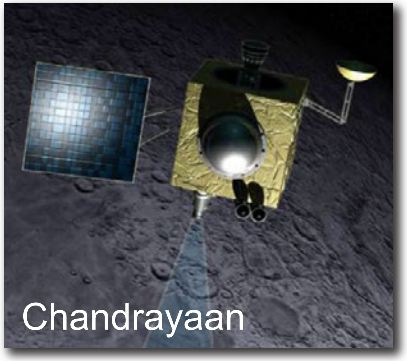
Human planetary exploration



Jack Schmitt & Lunar Roving Vehicle
Apollo 17 (1972)

What’s changed since Apollo?


Kaguya


Chandrayaan

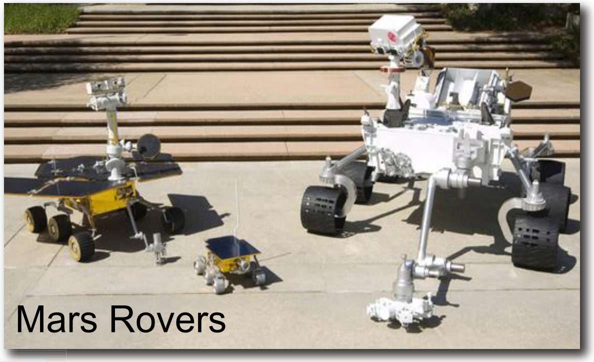

LRO


Space Station


Phoenix


Robonaut 2


LCROSS

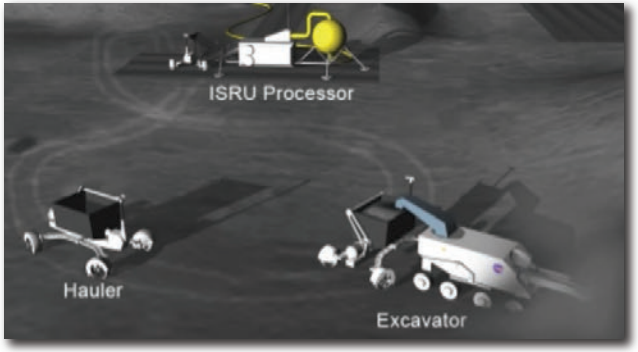

Mars Rovers


ATHLETE, K10, Chariot

Robots for human exploration

Robots before crew

- Prepare for subsequent human mission
- Scouting, prospecting, etc.
- Site preparation, equipment deployment, infrastructure setup, etc.



Robots supporting crew

- Parallel activities and real-time support
- Inspection, mobile camera, etc.
- Heavy transport & mobility

Robots after crew

- Perform work following human mission
- Follow-up and "caretaking" work
- Close-out tasks, maintenance, etc.

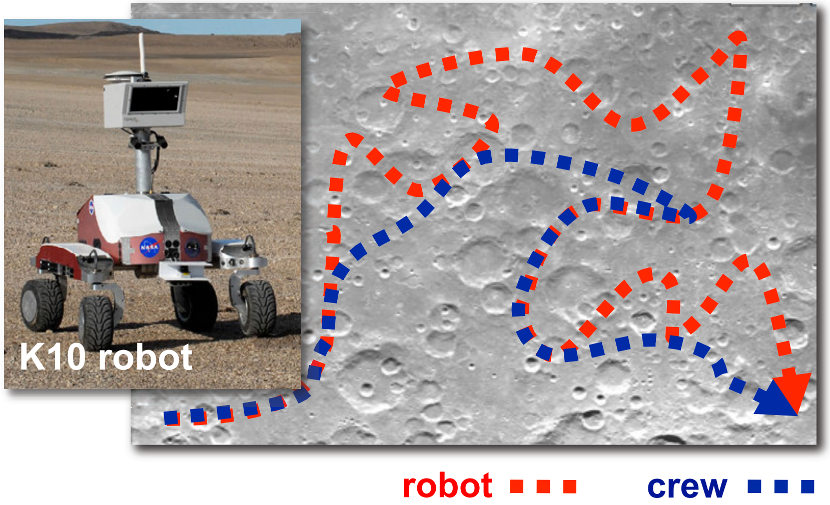
Robotic Recon Project

Objectives

- Assess value of robotic recon
- Study coordinated human-robot field exploration
- Fold lessons learned into lunar surface science ops concepts

Results

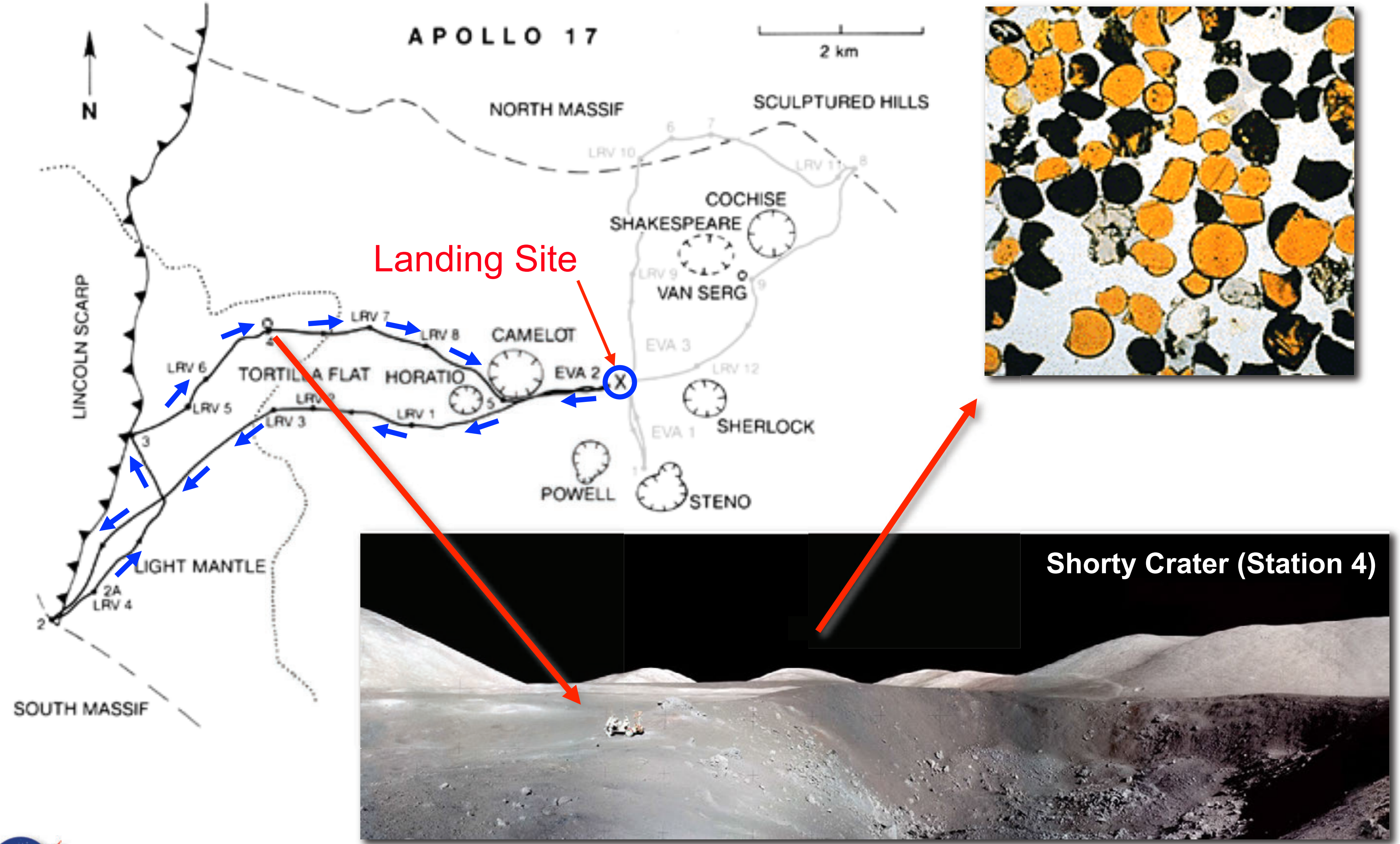
- Captured requirements (instruments, comm, nav, etc.) for robotic recon
- Assessed impact of robotic recon on traverse planning & crew productivity
- Learned how to improve human productivity & science return




Space Exploration Vehicle (SEV)

M. Bualat et al. (2011) **“Robotic recon for human exploration: method, assessment, and lessons learned”**. GSA special paper 483.

Why is recon useful?

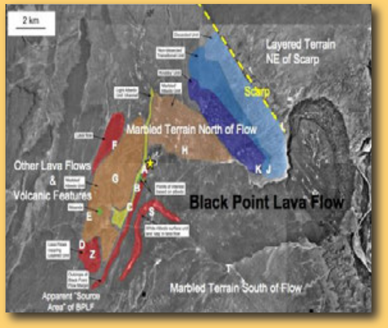


Landing Site

Shorty Crater (Station 4)

Field experiment (2009)

Pre-Recon



Mar 1 – June 1

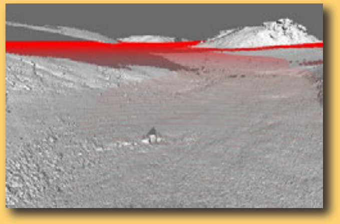
- Satellite images
- Geologic map

Robot Mission

June 14 – 26

- K10 at BPLF
- Ground control at NASA Ames

Pre-Crew



July 1 – Aug 15

- Recon images
- Terrain models

Crew Mission

Aug 29 – Sep 3

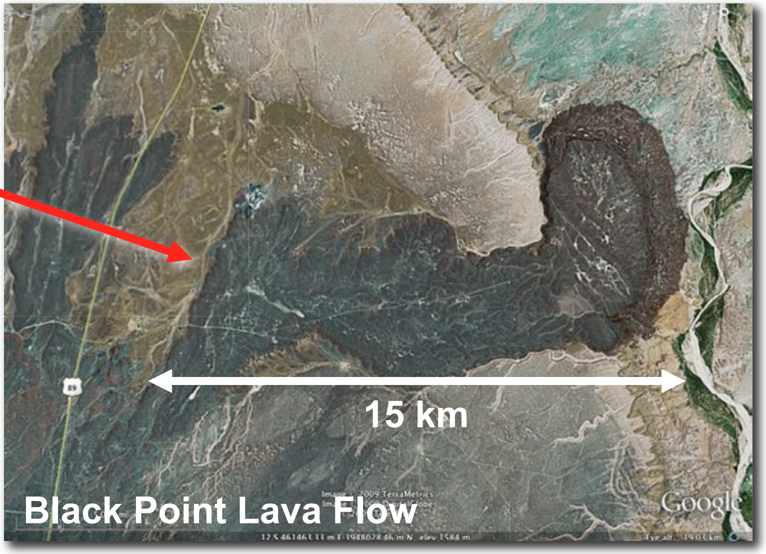
- SEV at Black Point
- Science backroom at Black Point

Lunar analog site

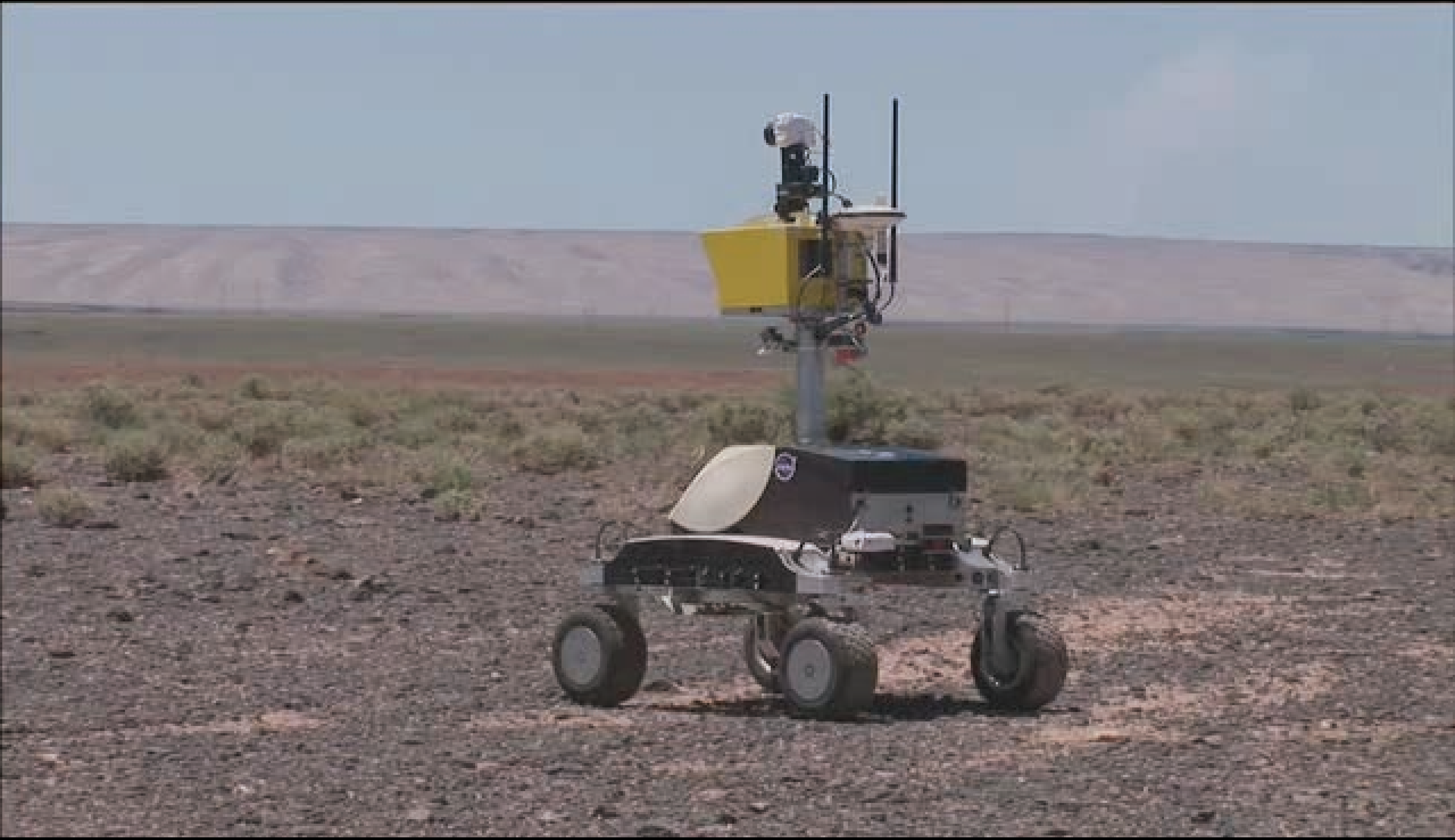
Black Point Lava Flow

- 65 km N of Flagstaff, AZ
- Analog of the “Straight Wall” (Mare Nubrium / Rupes Recta)
- Basaltic volcanic rocks & unit contacts

The “Straight Wall”



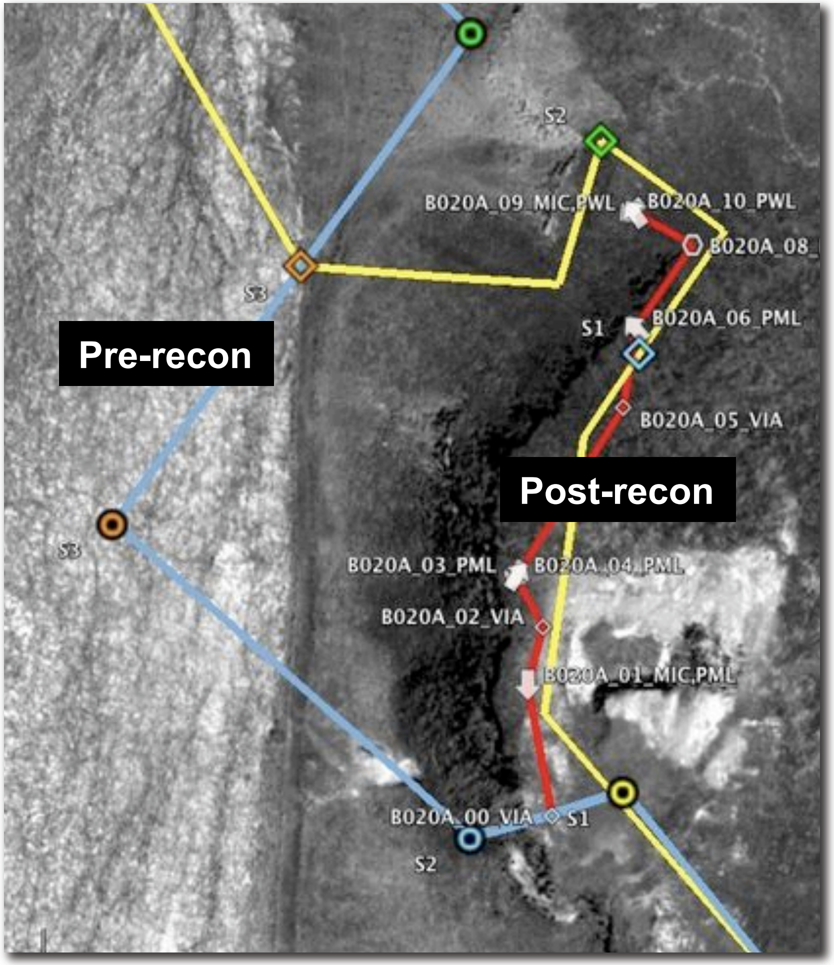
Black Point Lava Flow



Robotic recon results

“West” region

- **Pre-recon** traverse plan was designed to be **Apollo-like**
    - Rapid area coverage (visit 5 hypothesized geologic units)
    - Single visit / sortie
- **Post-recon** traverse plan is **significantly** different
    - More flexible & adaptable
    - Recon data supports **real-time replanning** by crew
- Impact of recon
    - Reduced science uncertainty
    - Improved target prioritization



T. Fong et al. (2010) **“Assessment of robotic recon for human exploration of the Moon”**. Acta Astronautica 67 (9-10)

Robotic Follow-up Project

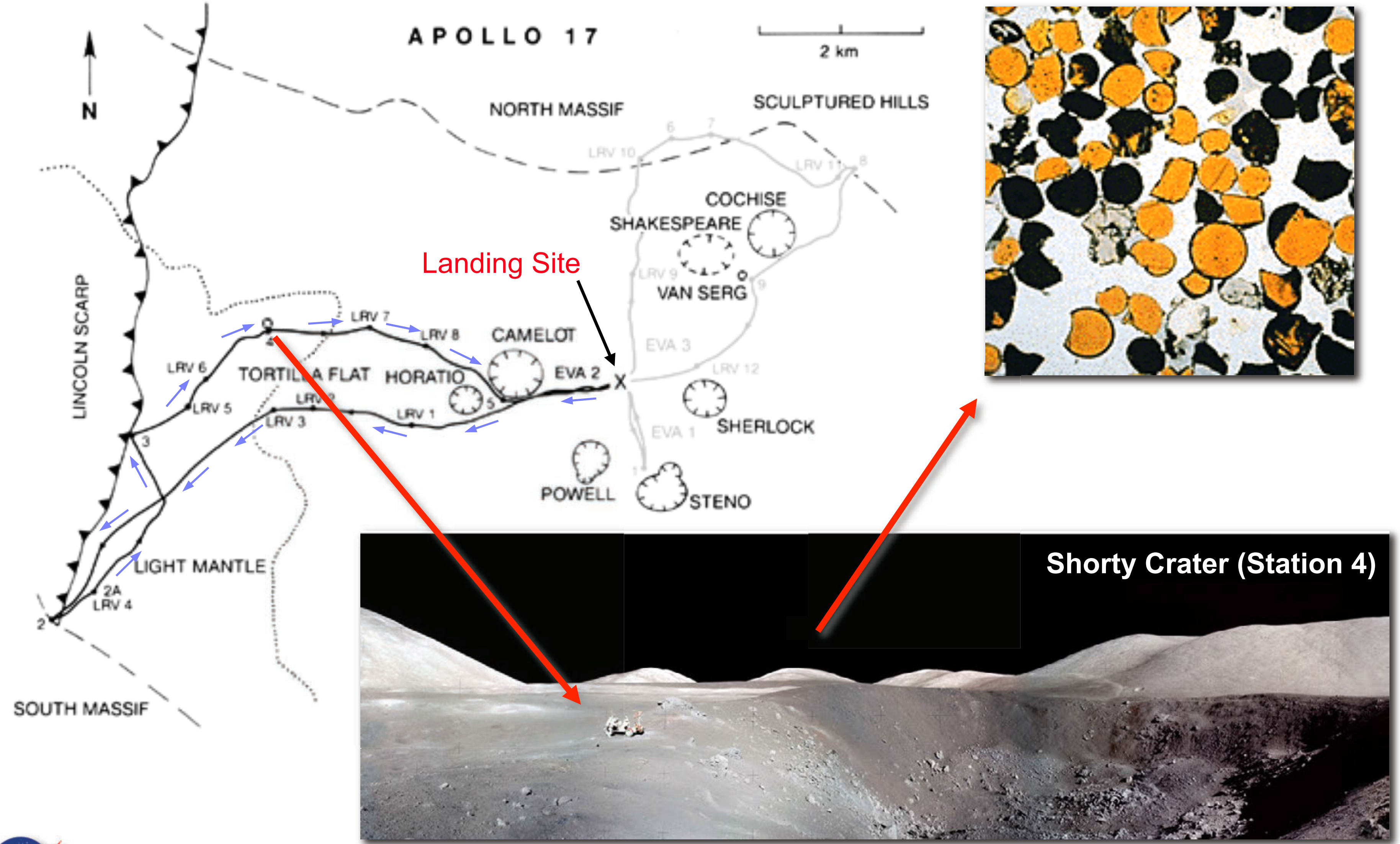
An exploration problem

- Never enough time for field work
- “If only I could have…”
    - More observations
    - Additional sampling
    - Complementary & supplementary work

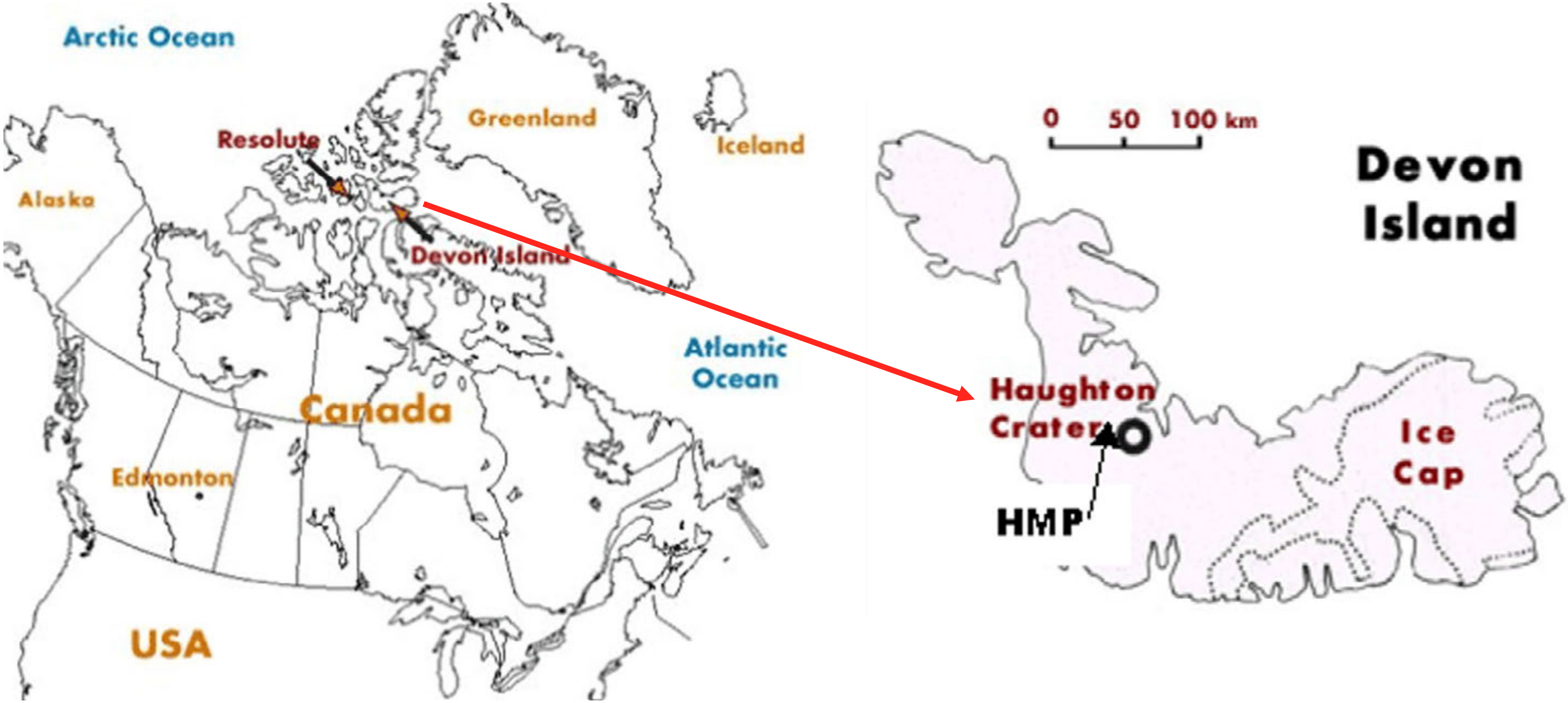
The solution

- Use robots to “follow-up” after human mission is completed
- Augment human field work with additional robot activity
- Use robots for work that is tedious or unproductive for humans

Why is follow-up useful?



Lunar analog site



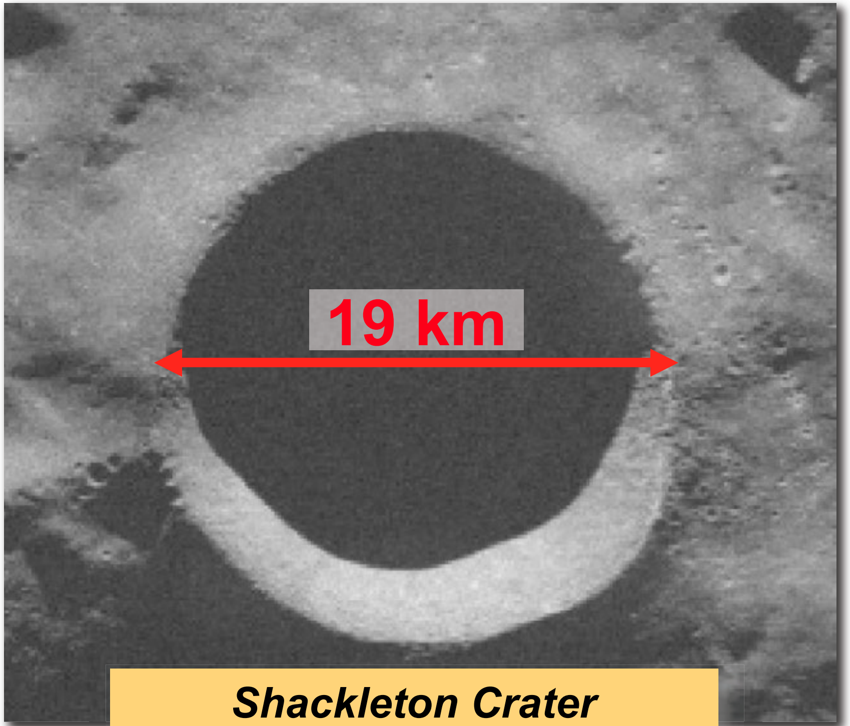
Haughton Crater

- 20 km diameter impact structure
- ~39 million years ago (Late Eocene)
- Devon Island: 66,800 sq. km (largest uninhabited island on Earth)

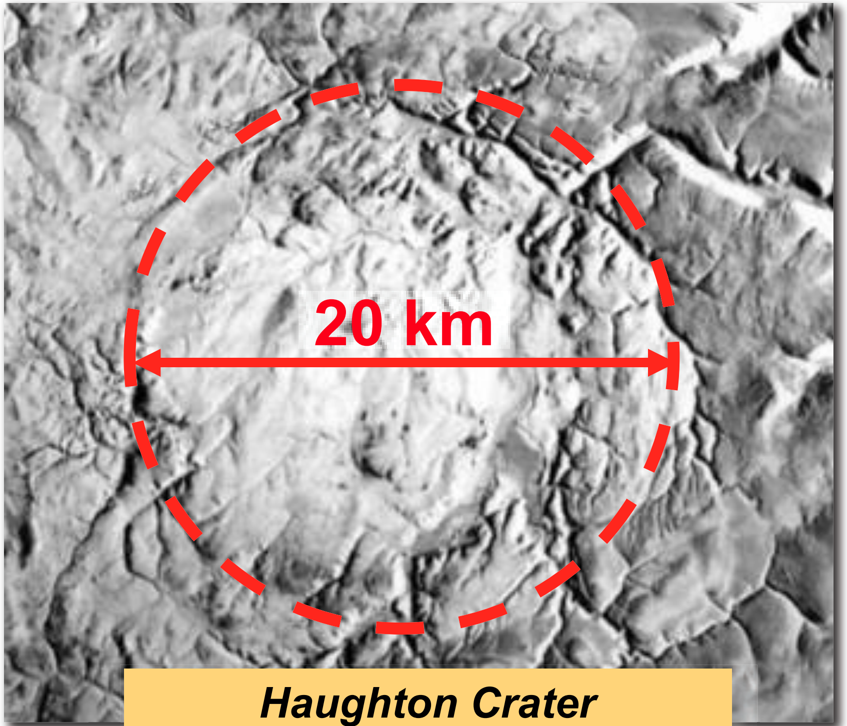
Haughton Crater

Haughton Crater
(75º 22’ N, 89º 41’ W)

Haughton Crater



Shackleton Crater
2005 Arecibo radar image



Haughton Crater
radar image

- Polar impact structures: mixed impact rocks & ejecta blocks
- Subsurface water ice
- Remote, isolated, difficult to access

Crew mission (July 2009)

Mark Helper and Pascal Lee

Essam Heggy and Pascal Lee

Geologic Mapping

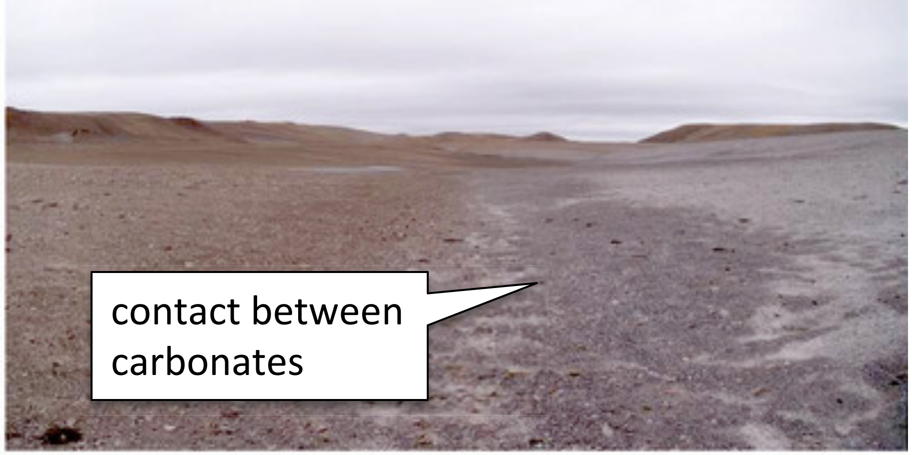
- Document geologic history, structural geometry & major units
- Example impact breccia & clasts
- Take photos & collect samples

Geophysical Survey

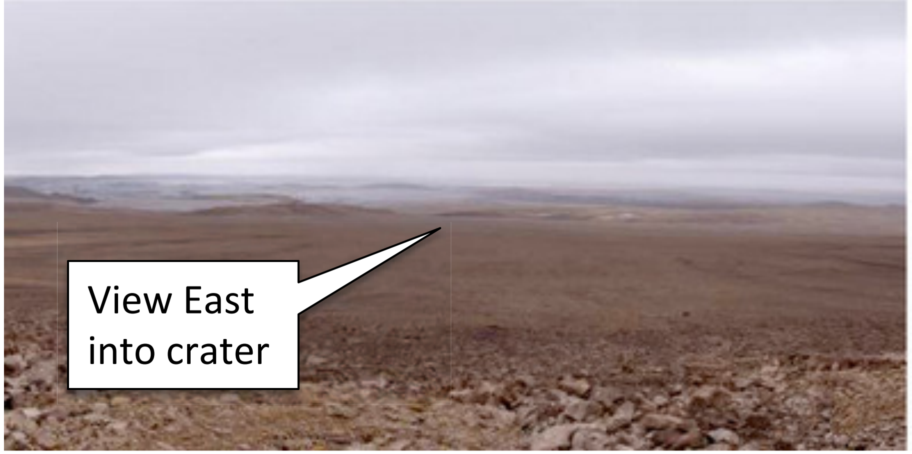
- Examine subsurface structure
- 3D distribution of buried ground ice in permafrost layer
- Ground-penetrating radar: manual deploy, 400/900 MHz

Geologic mapping results

stratified sediments



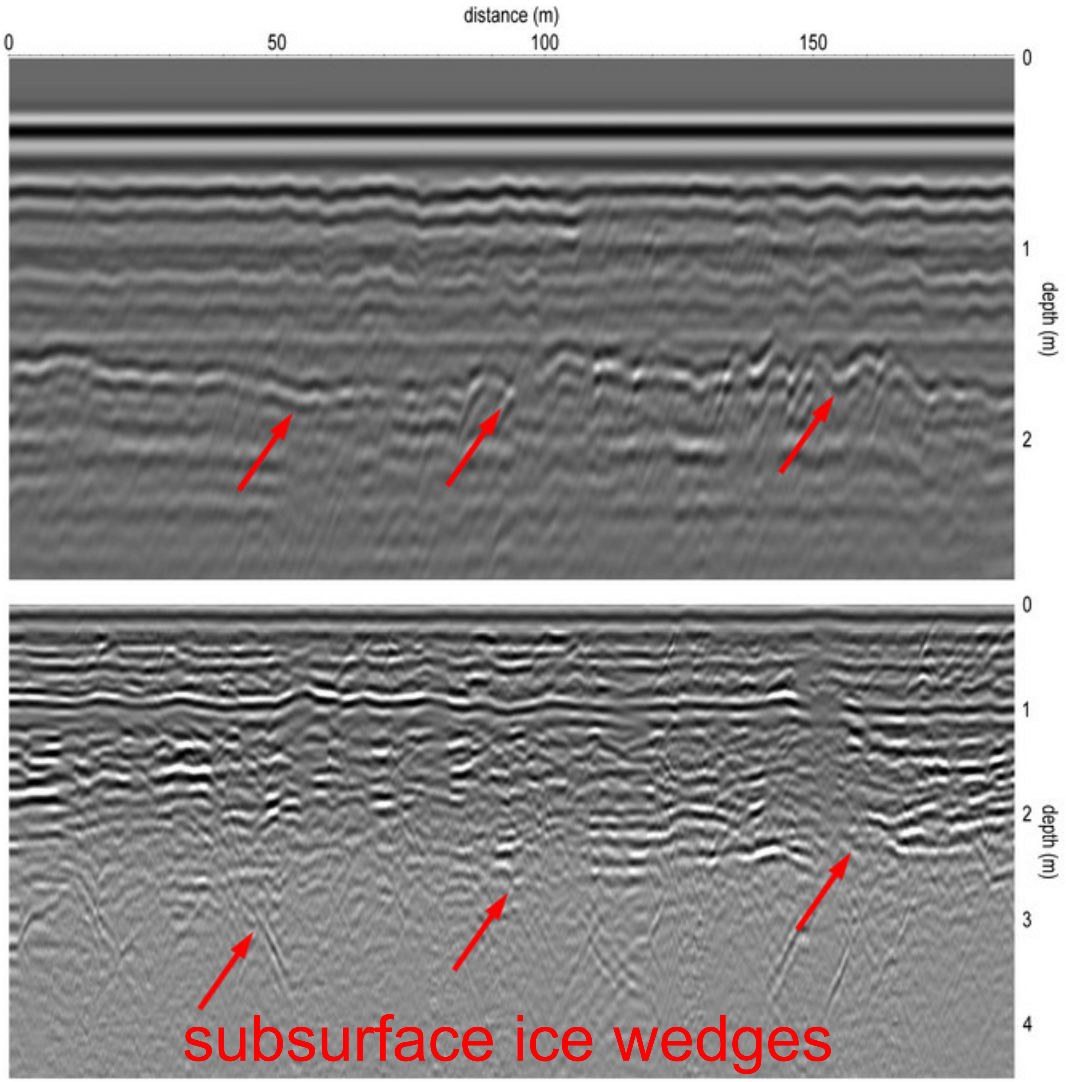
contact between carbonates



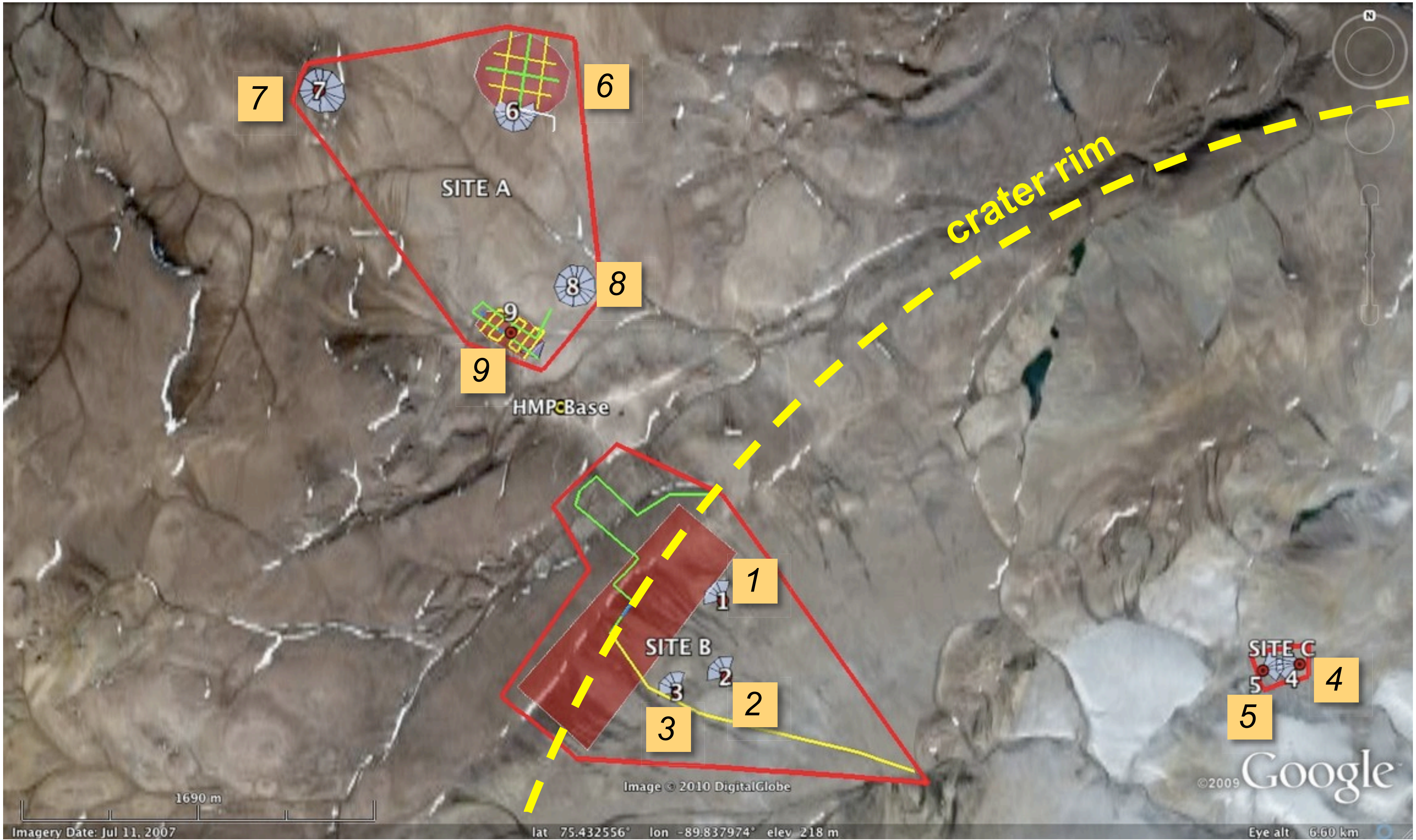
View East into crater

Gray carbonate breccia

Geophysical survey results



Robotic follow-up plan

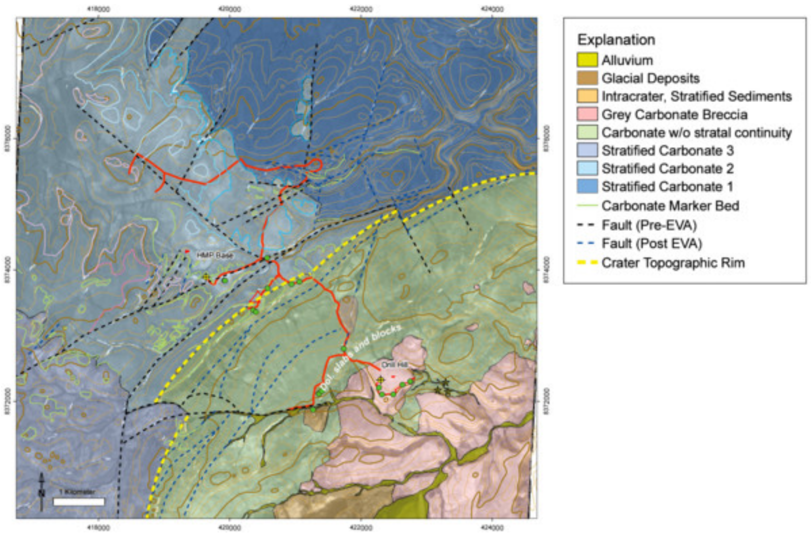



NASA

Robotic follow-up results

Geologic Mapping

- Verified the geologic map in multiple locations
- Amended the geologic map in multiple locations
- In some places, robot data was ambiguous, or lacked sufficient detail to re-interpret the map



Geophysical Survey

- Enabled study (correlation of surface & subsurface features) of terrain "polygons"
- Determined average depth of subsurface ice layer and features (ice wedges)

T. Fong, M. Bualat, et al. (2010) **"Robotic follow-up for human exploration"**. AIAA Space Conf.

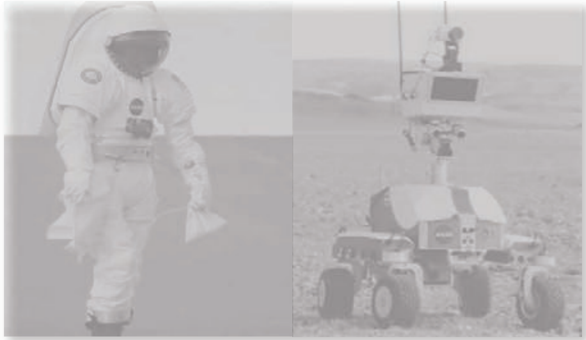
Research @ NASA Ames

Part 1: Communication

- Signaling for non-humanoid robots
- Convey robot state and intent using dynamic light and sound
- Ambient and active communication

Part 2: Coordination

- Achieve common (joint) objective
- Independent human and robot activities
- Robots work before, in parallel (loosely coupled) and after humans



Part 3: Collaboration

- Humans support autonomous robots
- Focus on cognitive tasks (planning, decision making, etc)
- Human-robot team may be distributed

Human-robot collaboration

Our focus

- Study how **humans can remotely support robots**
- Address the many **anomalies**, **corner cases**, and **edge cases** that require unique solutions, 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.

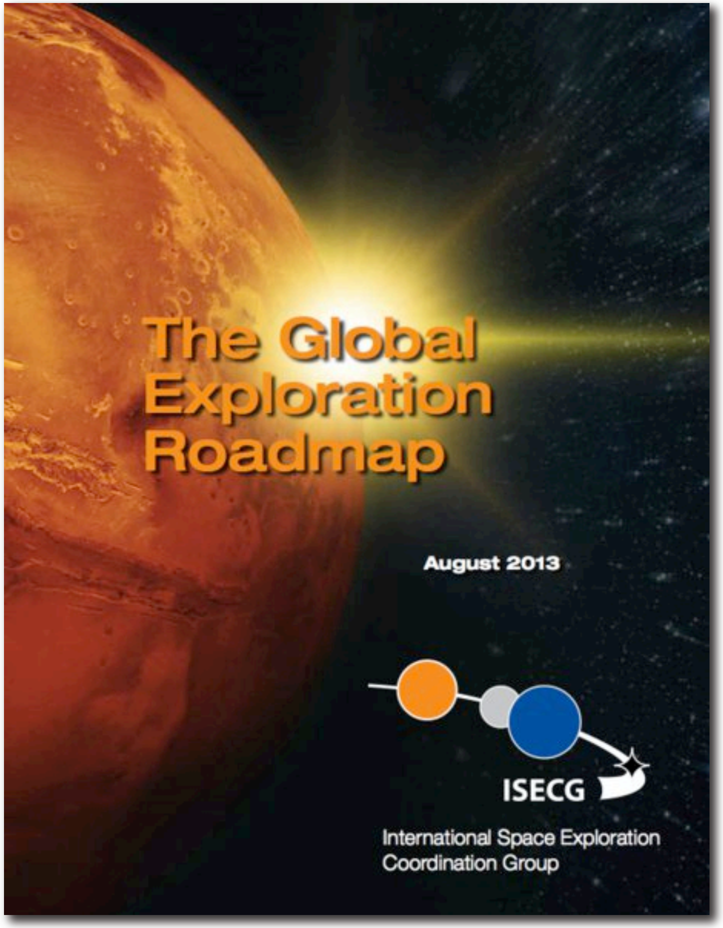
Global Exploration Roadmap (2013)

Human-Robotic Partnership (p. 22)

Tele-Presence

Tele-presence can be defined as tele-operation of a robotic asset on a planetary surface by a person who is relatively close to the planetary surface, perhaps orbiting in a spacecraft or positioned at a suitable Lagrange point. Tele-presence is a capability which could significantly enhance the ability of humans and robots to explore together, where the specific exploration tasks would benefit from this capability. These tasks could be characterized by:

- High-speed mobility
- Short mission durations
- Focused or dexterous tasks with short-time decision-making
- Reduced autonomy or redundancy on the surface asset
- Contingency modes/failure analysis through crew interaction



The Global Exploration Roadmap

August 2013

ISECG

International Space Exploration Coordination Group

Surface telerobotics project

Key Points

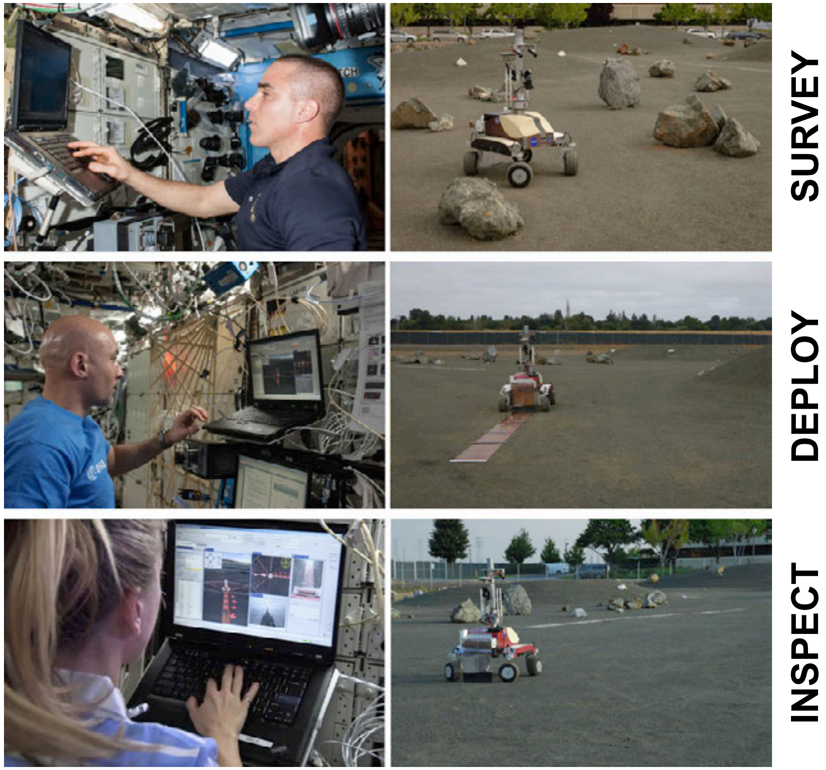
- Demo **crew-control** surface telerobotics (planetary rover) from ISS
- Test **human-robot conops** for future exploration mission
- Obtain **baseline engineering data** (robot, crew, data comm, task, etc)

Implementation

- Lunar libration mission simulation
- Astronaut on ISS (in USOS)
- K10 rover in NASA Ames Roverscape

ISS Testing (Expedition 36)

June 17, 2013 – **C. Cassidy**, survey
July 26, 2013 – **L. Parmitano**, deploy
Aug 20, 2013 – **K. Nyberg**, inspect



- **Human-robot mission sim**: site survey, telescope deployment, and inspection
- **Telescope proxy**: Kapton polyimide film roll (no antenna traces, electronics, or receiver)
- **3.5 hr per crew session** ("just in time" training, system checkout, ops, & debrief)
- **Robot ops**: manual control (discrete commands) and supervisory control (task sequence)

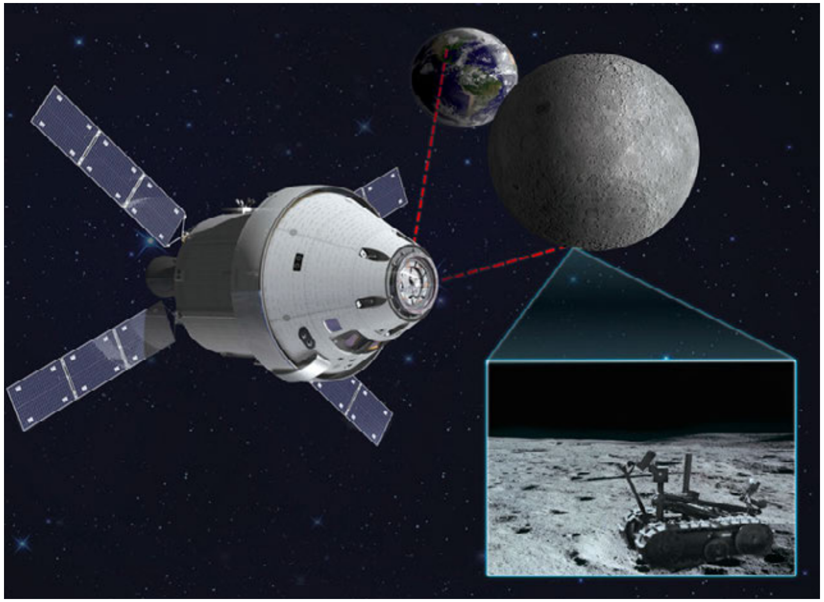
“Fastnet” lunar libration point mission

Orion MPCV at Earth-Moon L2 (EM-L2)

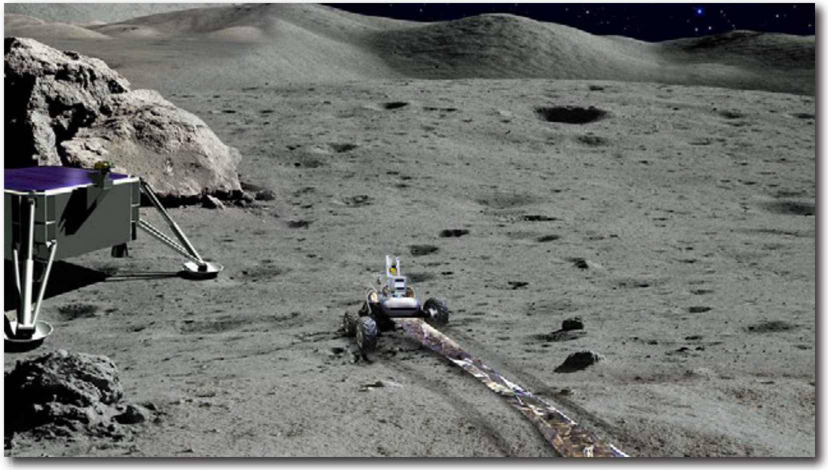
- 60,000 km beyond lunar farside
- Allows station keeping with minimal fuel
- Crew remotely operates robot
- Does not require human-rated lander

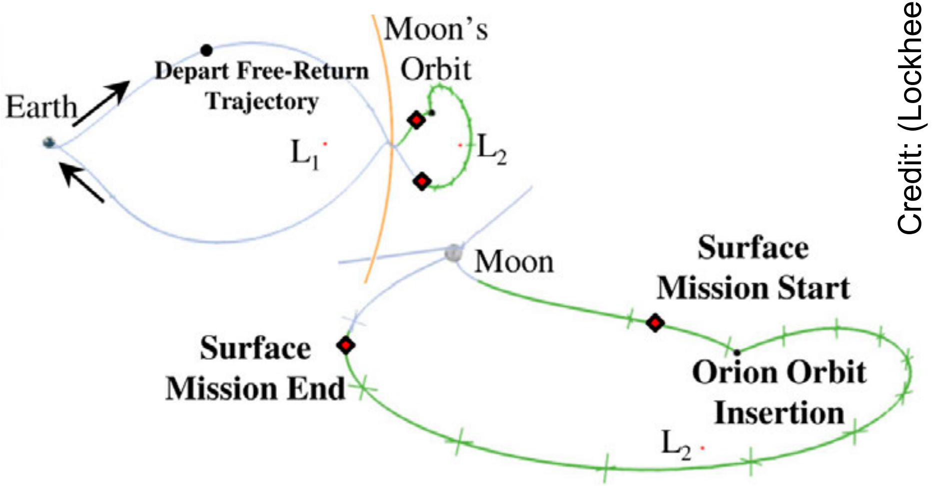
Human-robot conops

- Crew remotely operates surface robot from inside flight vehicle
- Crew works in shirt-sleeve environment
- Multiple robot control modes

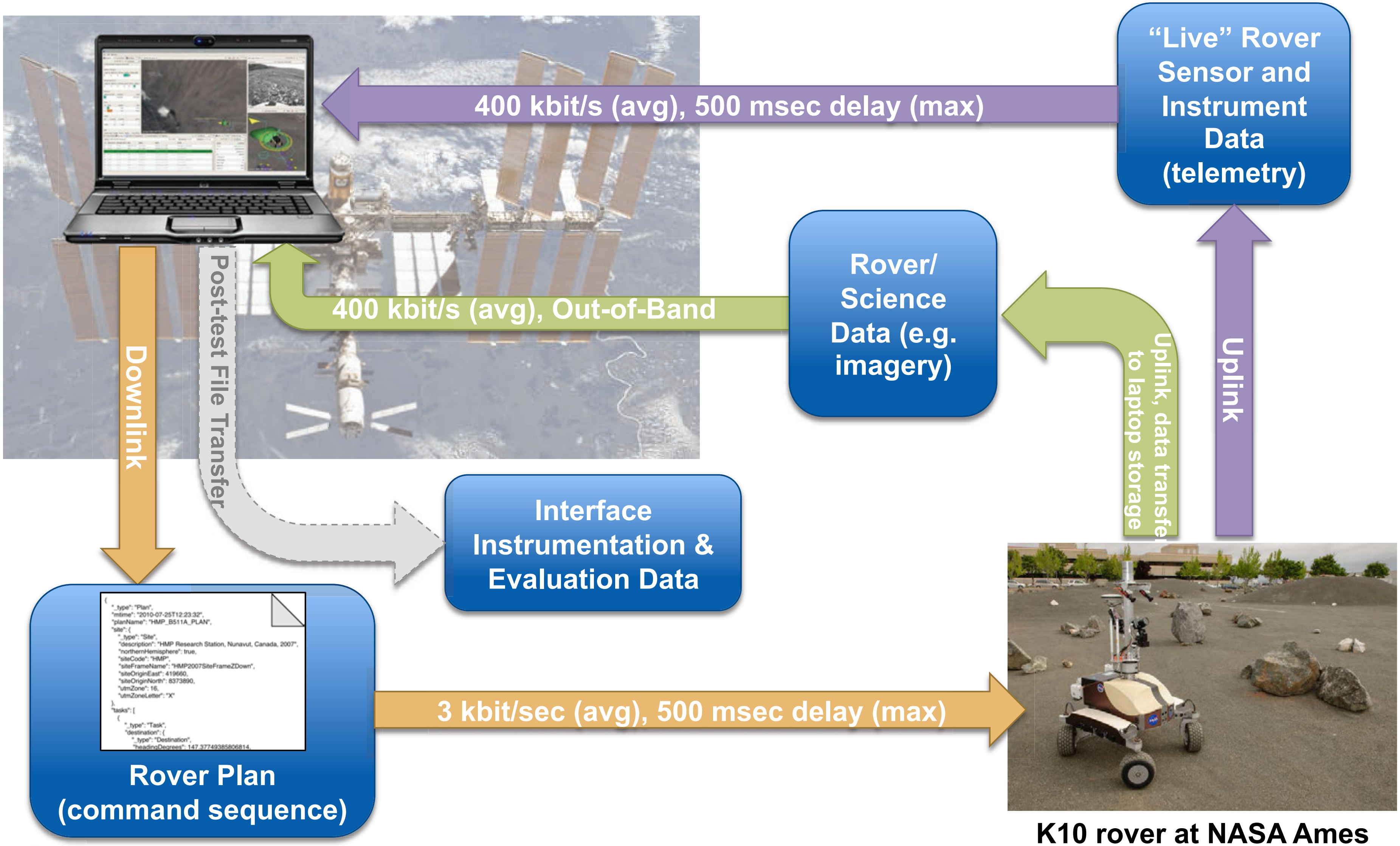


Credit: (Lockheed Martin / LUNAR)





ISS test setup



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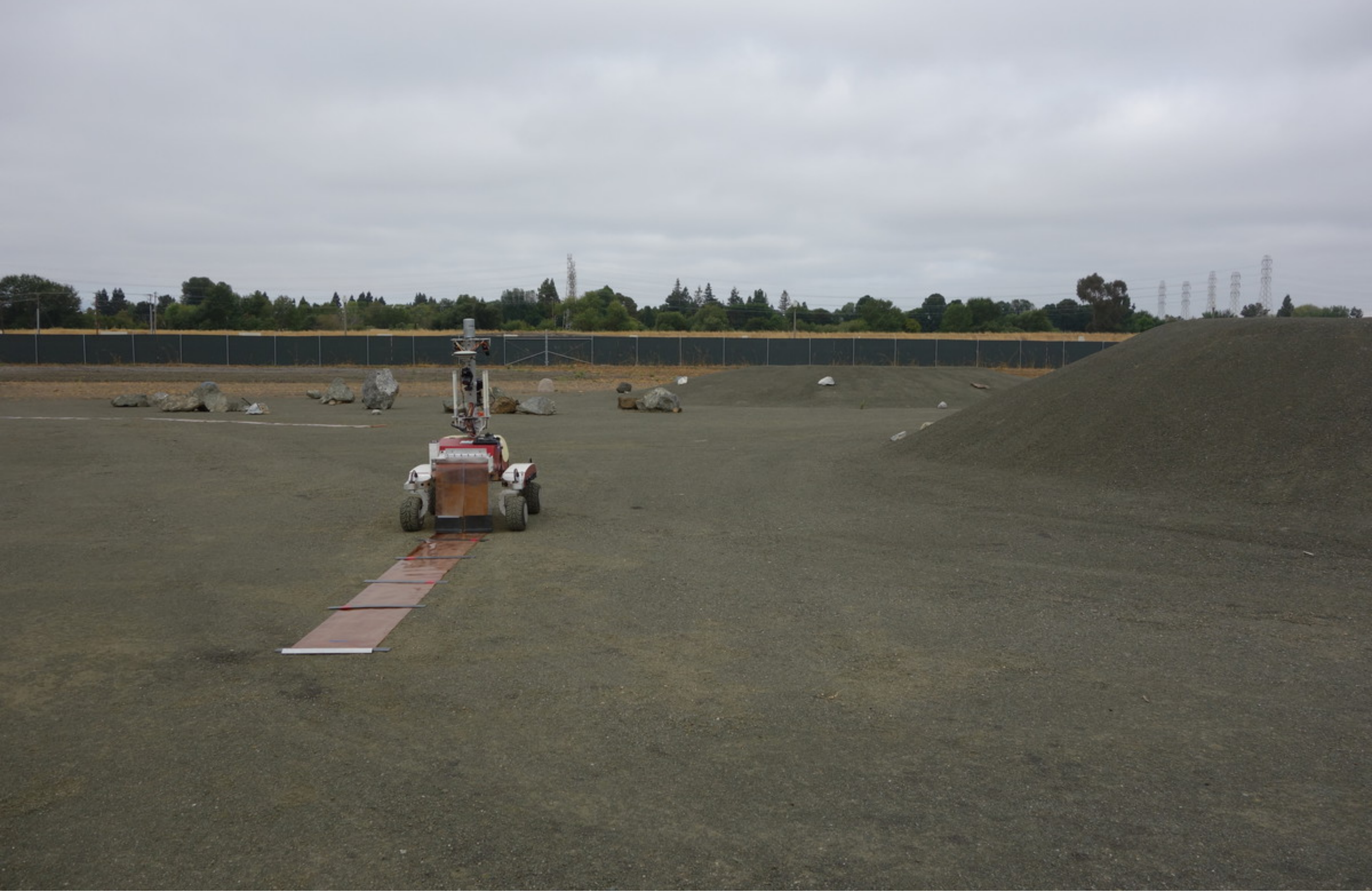
K10 rover at NASA Ames

Astronaut in space / Robot on Earth

Crew Session #1 – **K10 performing surface survey (2013-06-17)**

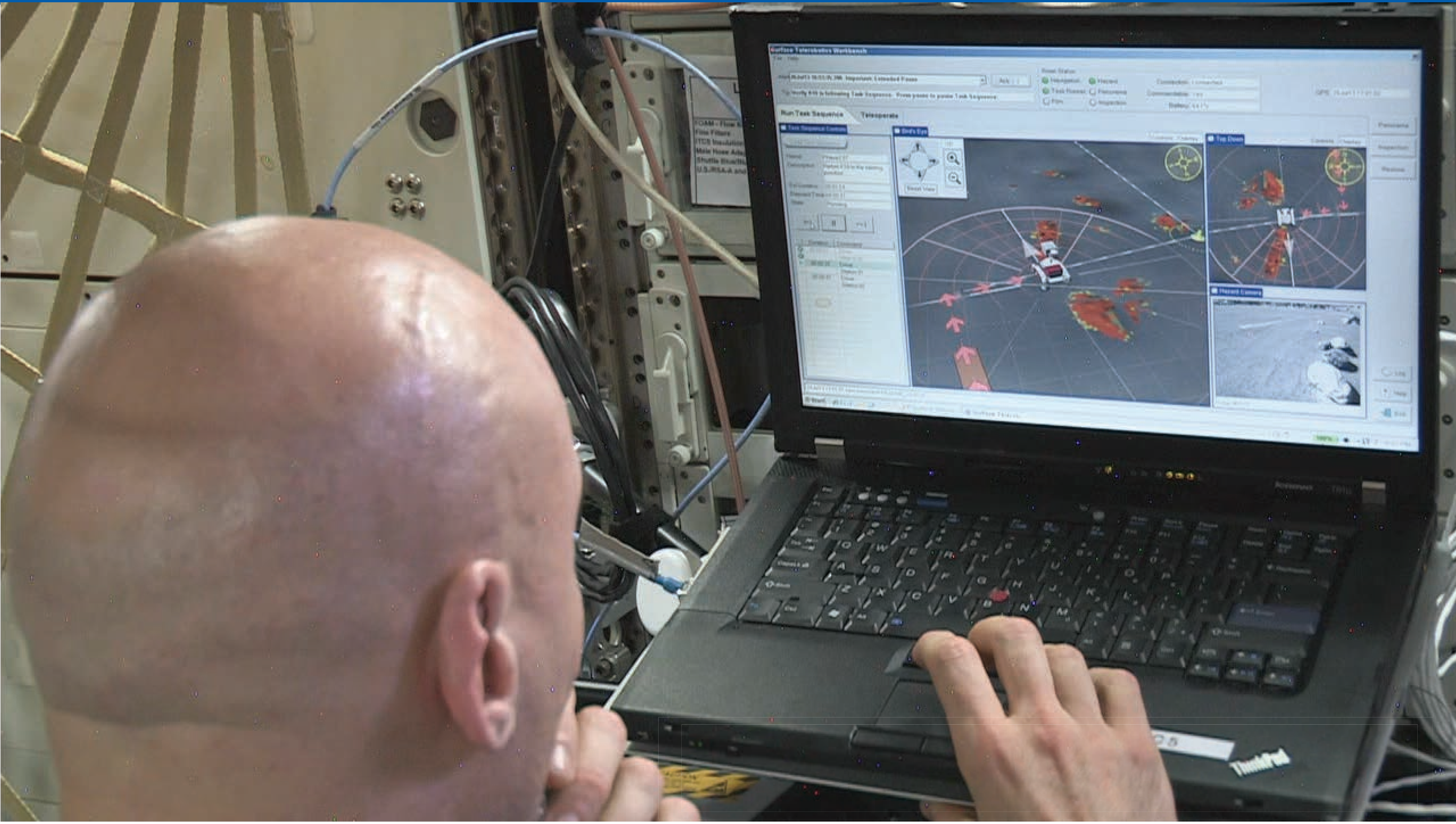
Chris Cassidy uses the "Surface Telerobotics Workbench" to remotely operate K10 from the ISS



Crew Session #2 – **K10 deploying simulated polymide antenna (2013-07-26)**

ISS Mission Control (MCC-H) during Surface Telerobotics test
View of robot interface and K10 at ARC

Crew control of K-10 rover



Deployed simulated polymide antenna (three “arms”)

Crew Session #3 – **Karen Nyberg remotely operates K10 (2013-08-20)**

K10 documenting simulated polymide antenna

Assessment approach

Metrics

- **Mission Success:** % task sequences: completed normally, ended abnormally or not attempted; % task sequences scheduled vs. unscheduled
- **Robot Utilization:** % time robot spent on different types of tasks; comparison of actual to expected utilization
- **Task Success:** % completed normally, ended abnormally or not attempted; % that ended abnormally vs. unscheduled task sequences
- **Contingencies:** Mean Time To Intervene, Mean Time Between Interventions
- **Robot Performance:** expected vs. actual execution time on tasks

Data Collection

automatic

- **Data Communication:** direction (up/down), message type, total volume, etc.
- **Robot Telemetry:** position, orientation, power, health, instrument state, etc.
- **User Interfaces:** mode changes, data input, access to reference data, etc.
- **Robot Operations:** start, end, duration of planning, monitoring, and analysis
- **Crew Questionnaires:** workload (Bedford Scale), situation awareness (SAGAT)

M. Bualat, D. Schreckenghost, et al. (2014) **"Results from testing crew-controlled surface telerobotics on the International Space Station"**. 12th I-SAIRAS

Human-robot collaboration

Productivity

- **Productive Time** (PT) = astronaut and robot performing tasks contributing to mission objectives
- **Overhead Time** (OT) = astronaut and robot are waiting
- **Work Efficiency Index (WEI) = Productive Time / Overhead Time**

Productivity	Total Phase Time	PT	OT	%PT	%OT	WEI
Survey	0:50:01	0:34:58	0:15:03	69.90	30.10	2.32
Deploy	0:46:19	0:28:00	0:18:19	60.45	39.55	1.53

Highly productive

Self-driving cars at NASA Ames

Public/private partnerships

- **Google** (2014-15): collaborative testing of sensors and vehicles
- **Nissan** (2014-17): cooperative software development

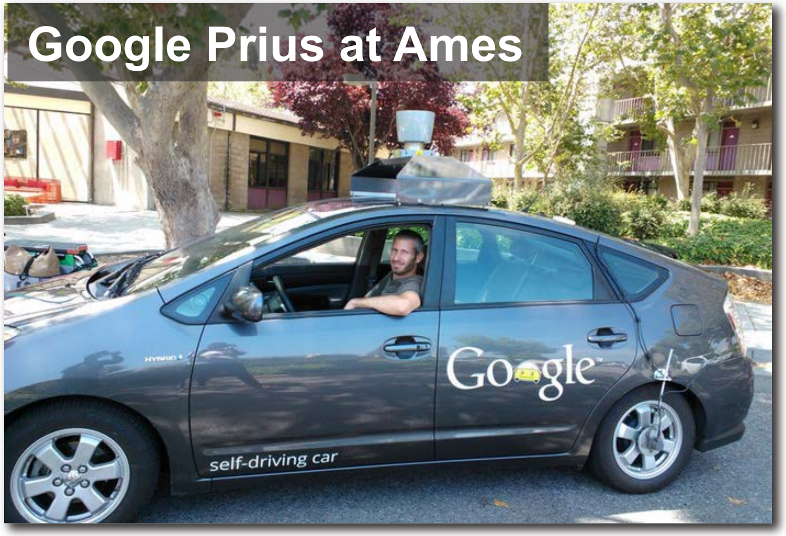
NASA interest

- Expand knowledge of commercial autonomous systems
- Develop protocols and best practices for safe testing of real-world autonomy
- Transfer NASA technology to terrestrial applications

Technology maturation

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


Nissan Leaf at Ames


Google Prius at Ames

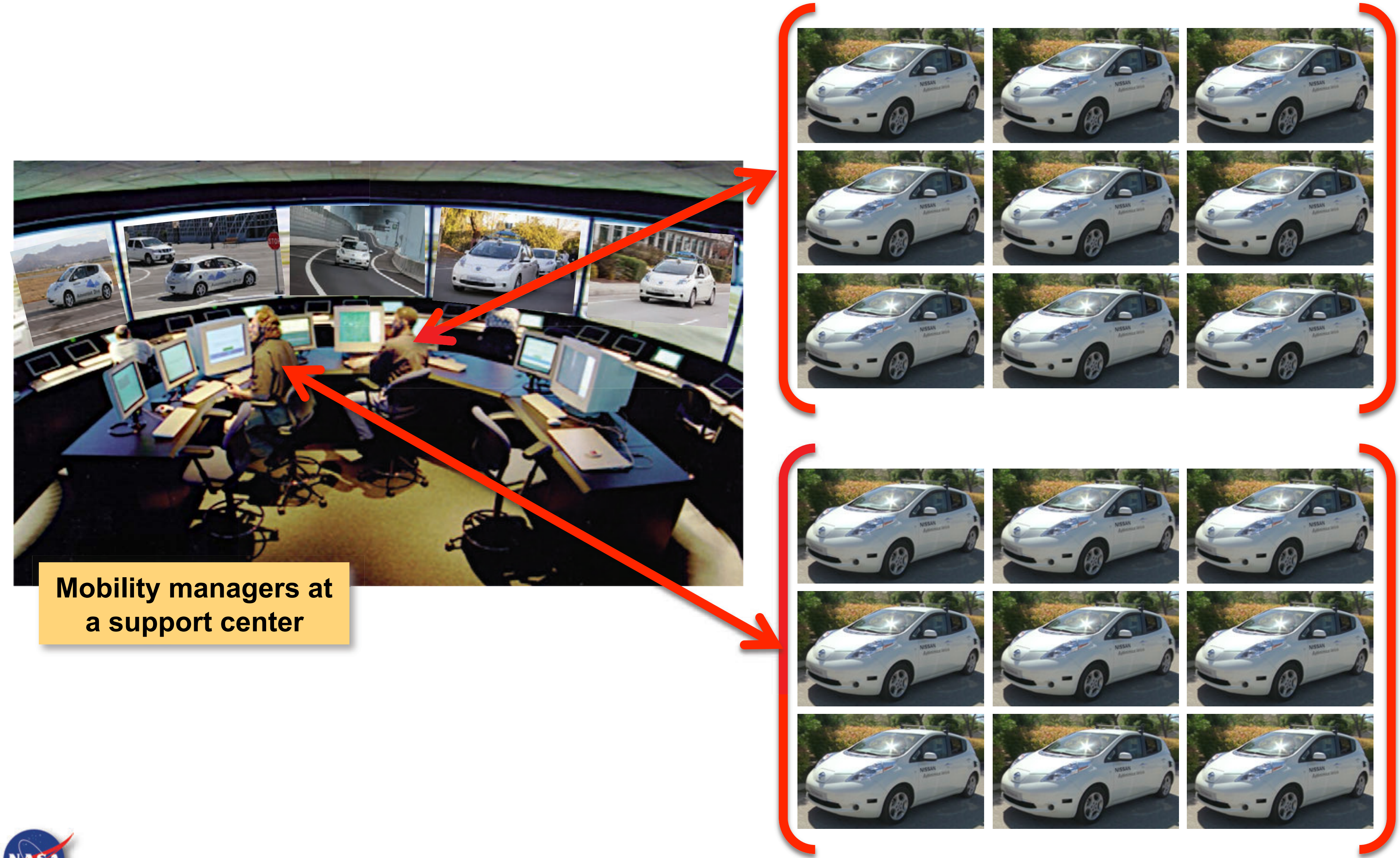
Imperfect vehicle autonomy

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.

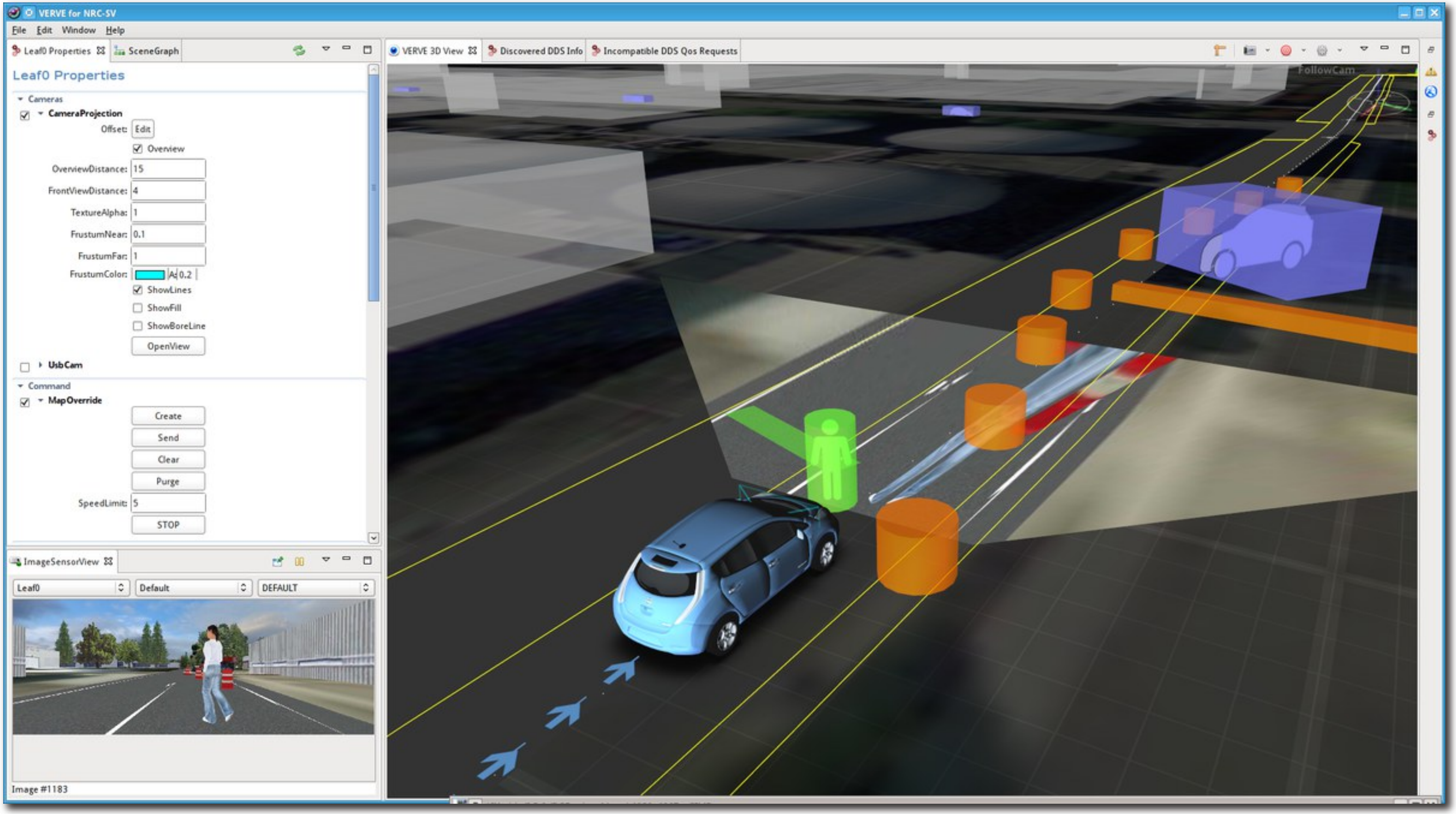
– Andrew Ng (Wired, 3/15/2016)

Human at work / Self-driving car on road



Mobility managers at a support center

Vehicle assist: Situation assessment



Leaf0 Properties

Cameras

☑ **CameraProjection**

Offset:

☑ Overview

OverviewDistance: 15

FrontViewDistance: 4

TextureAlpha: 1

FrustumNear: 0.1

FrustumFar: 1

FrustumColor: A: 0.2

☑ ShowLines

☐ ShowFill

☐ ShowBoreLine

☐ **UsbCam**

Command

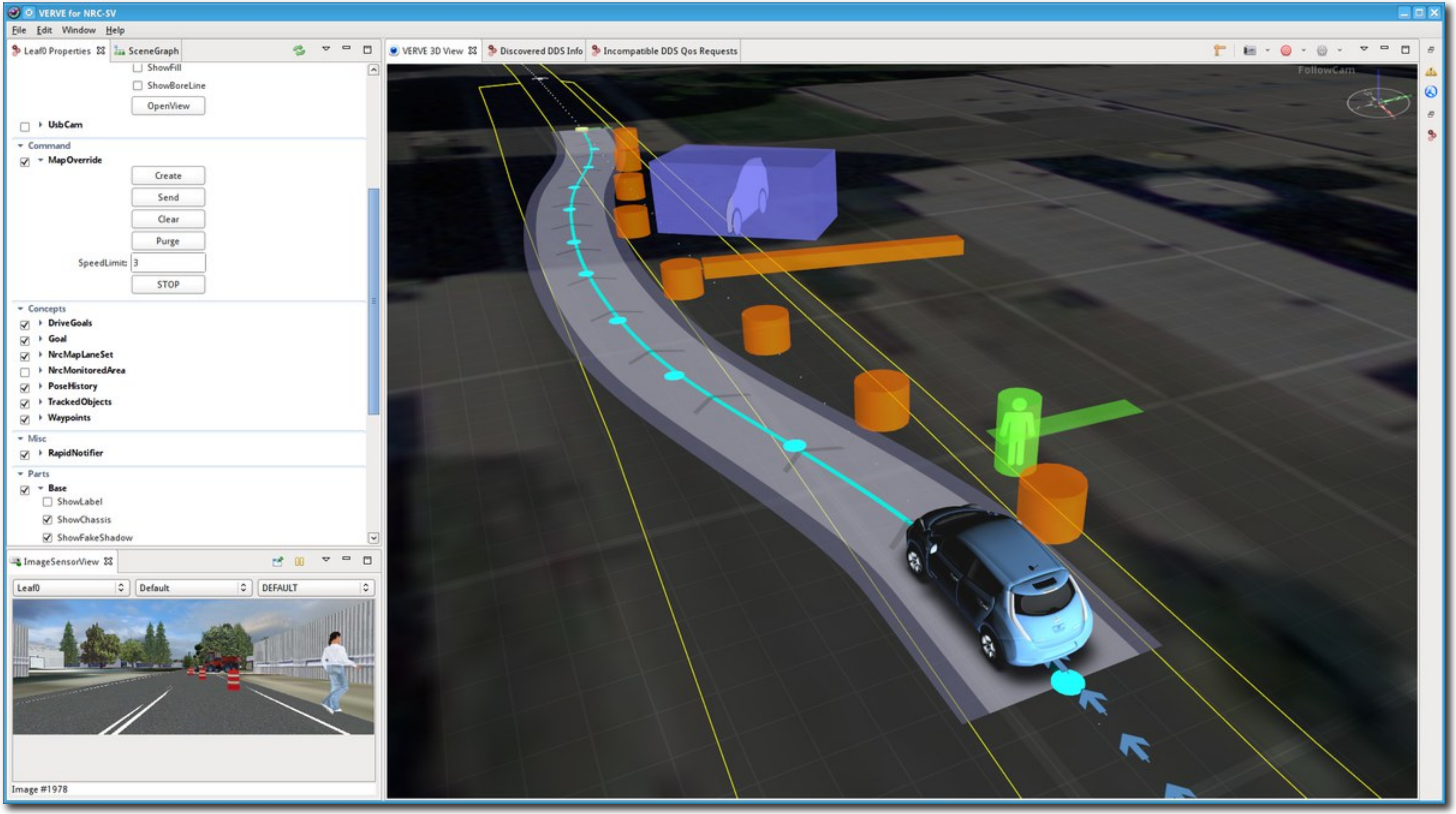
☑ **MapOverride**

SpeedLimit: 5

Leaf0 | Default | DEFAULT

Image #1183

Vehicle assist: High-level guidance



- ☐ ShowFill
- ☐ ShowBoreLine
- ☐ UsbCam

Command

- ☑ MapOverride

SpeedLimit: 3

Concepts

- ☑ DriveGoals
- ☑ Goal
- ☑ NrcMapLaneSet
- ☐ NrcMonitoredArea
- ☑ PoseHistory
- ☑ TrackedObjects
- ☑ Waypoints

Misc

- ☑ RapidNotifier

Parts

- ☑ Base
  - ☐ ShowLabel
  - ☑ ShowChassis
  - ☑ ShowFakeShadow

Leaf0 | Default | DEFAULT

CES 2017 demo

Building effective human-robot teams

Communication

- Design **appropriate signals** (compact, legible, etc) to convey robot intent, status, etc.
- Signals may need to vary based on distance, environment, situation, etc.
- Do not need natural language to be effective

Coordination

- Must **make it easy for humans to work with robot** (and vice versa)
- Human-robot teaming is not just side-by-side, closely coupled actions
- Consider how robots working **before**, in **support**, and **after** humans can be effective at achieving a goal

Collaboration

- Identifying and building upon **interdependence** is essential
- Not all tasks can be planned in advance -- teaming must support spontaneous actions
- An effective team **works together** to achieve a shared objective

Questions?

Intelligent Robotics Group
Intelligent Systems Division
NASA Ames Research Center

irg.arc.nasa.gov