Human-Robot Teaming:

From space robotics to self-driving cars

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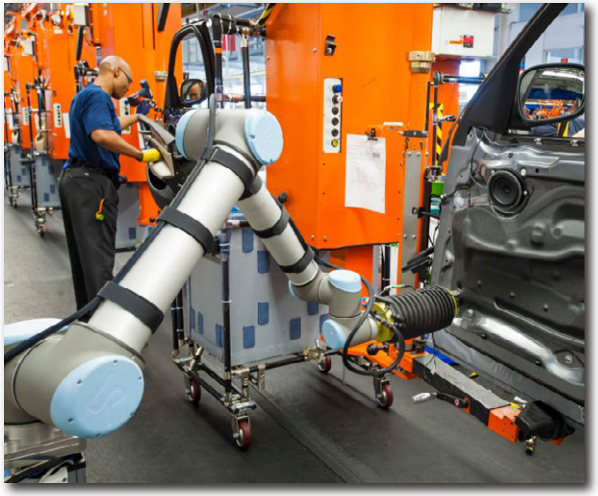
2018-12-02

Human-Robot Teams…



What is a team?

Teams are interdependent

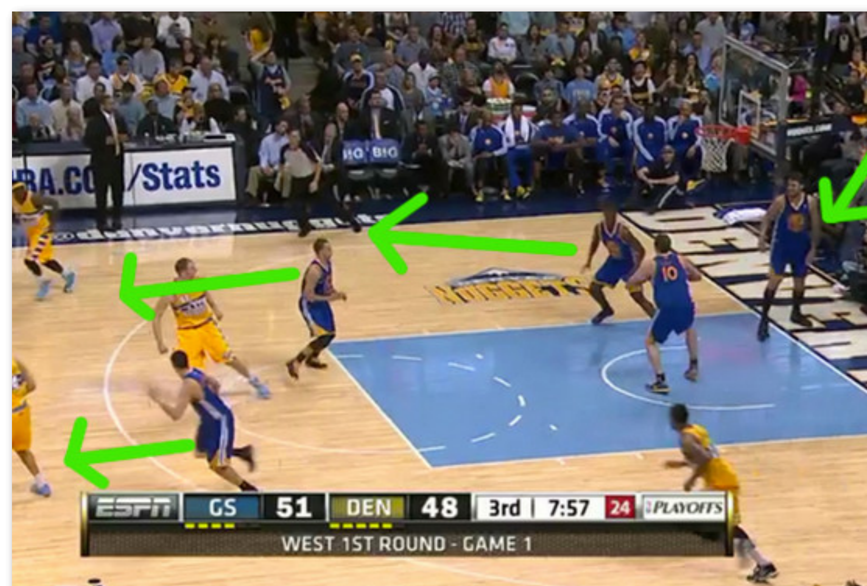
- Members share a common goal
- Group needs > individual need
- Common ground & trust

Norms

- Background (experience, training, knowledge, etc.)
- Organizational structure
- Work protocol (taskwork)

Cornerstones of teamwork

1. Communication
2. Coordination
3. Collaboration



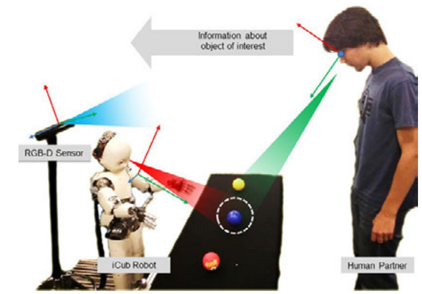
Communication

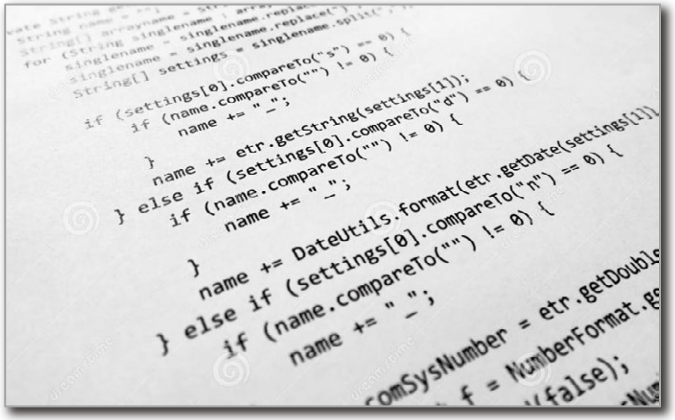
Signals

- 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





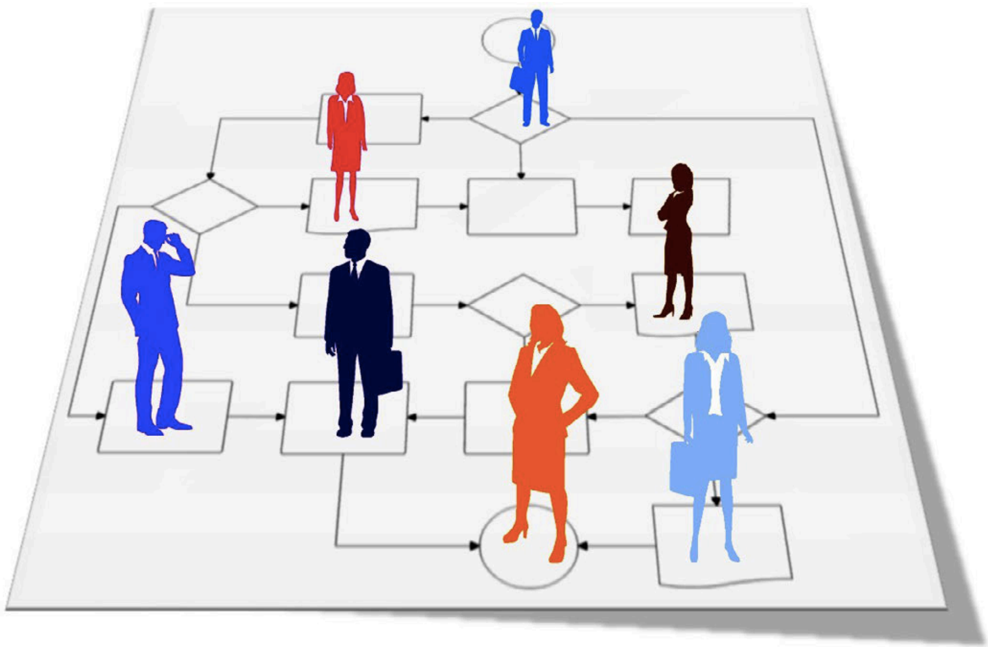
Coordination

"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



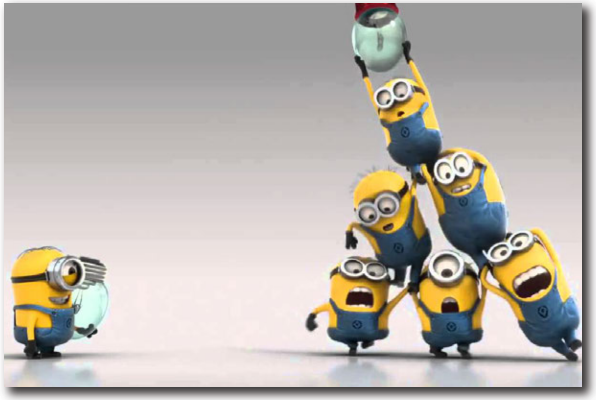
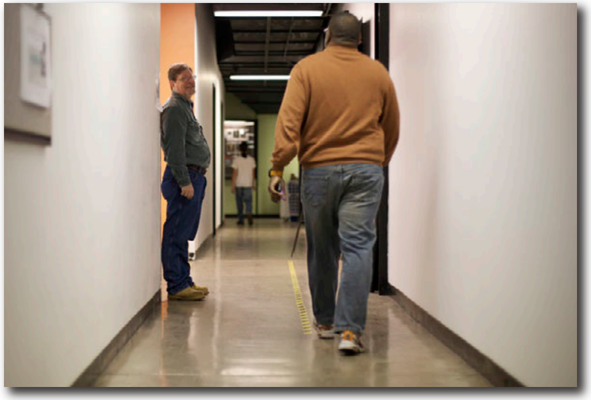
Collaboration

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.

Design considerations

Humans have limits

- Sensorimotor performance is not consistent, nor perfect
- Experience, knowledge, training, proficiency, fatigue, etc. are factors

Robots have 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

L. Ma, T. Fong, M. Micire, Y. Kim, and K. Feigh (2017). **"Human-robot teaming: concepts and components for design"**. Field & Service Robotics.

Research @ NASA Ames

Part 1: Communication

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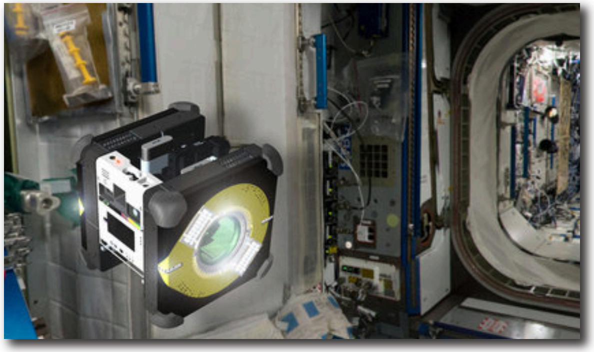
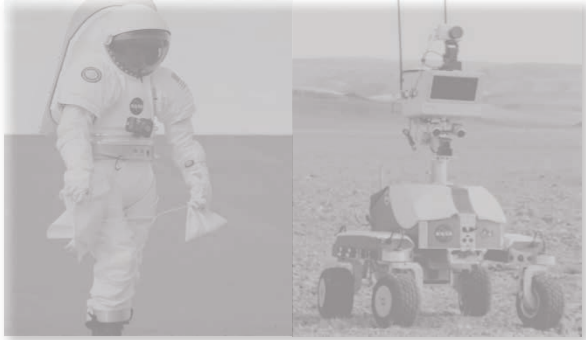
- Convey robot state and intent using dynamic light and sound
- Ambient and active communication



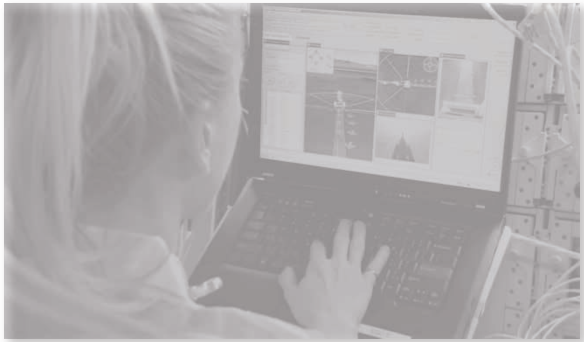
Part 2: Coordination

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



Part 3: Collaboration

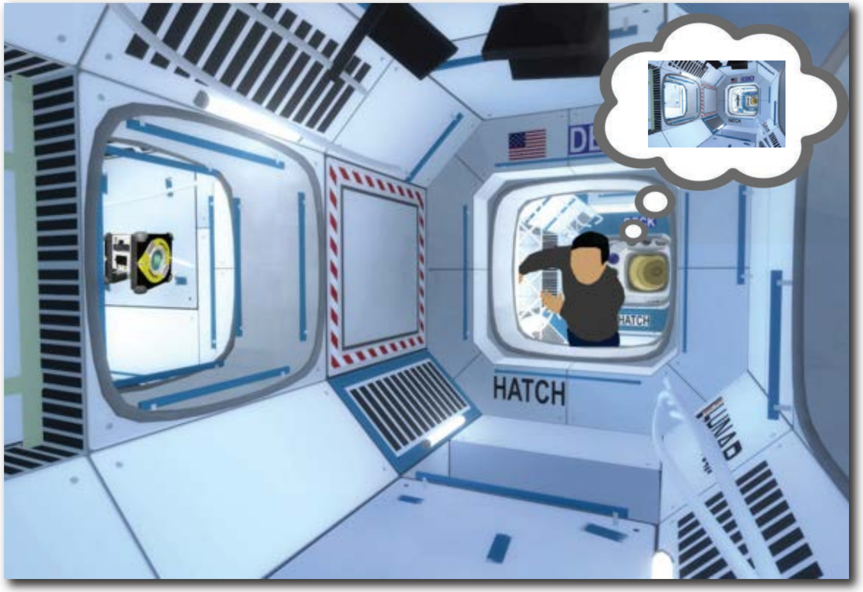
- Humans support autonomous robots
- Focus on cognitive tasks (planning, decision making, etc)
- Human-robot team may be distributed

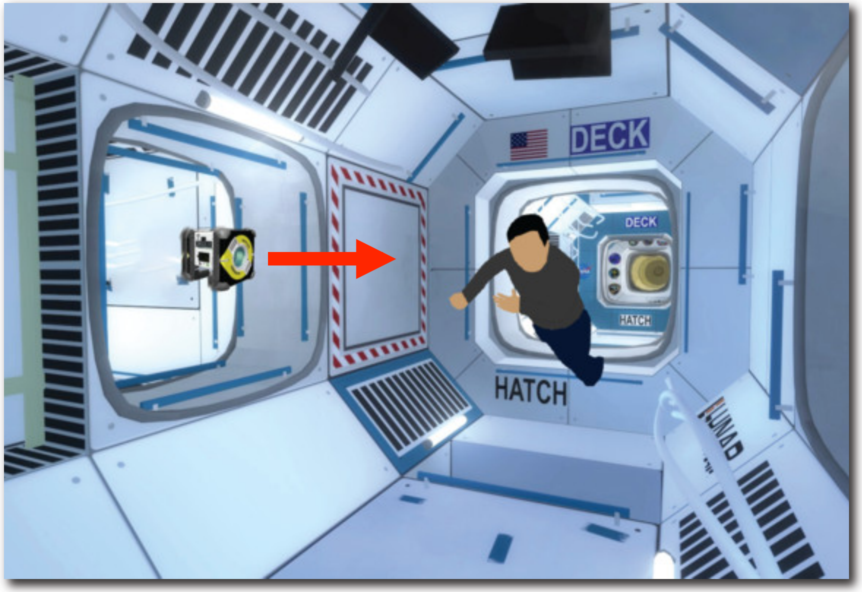


Motivation

Situation awareness (SA)

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

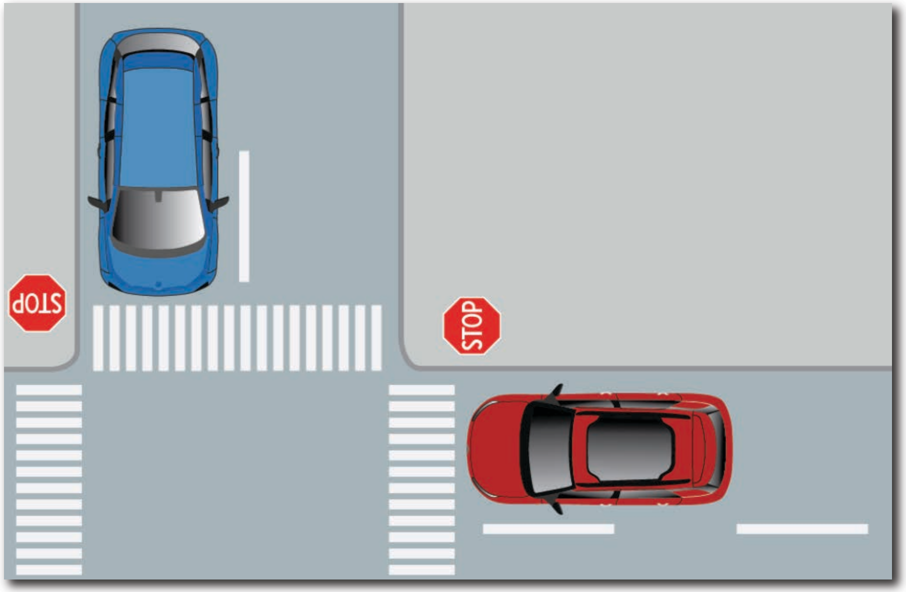




Motivation

Spatial negotiation

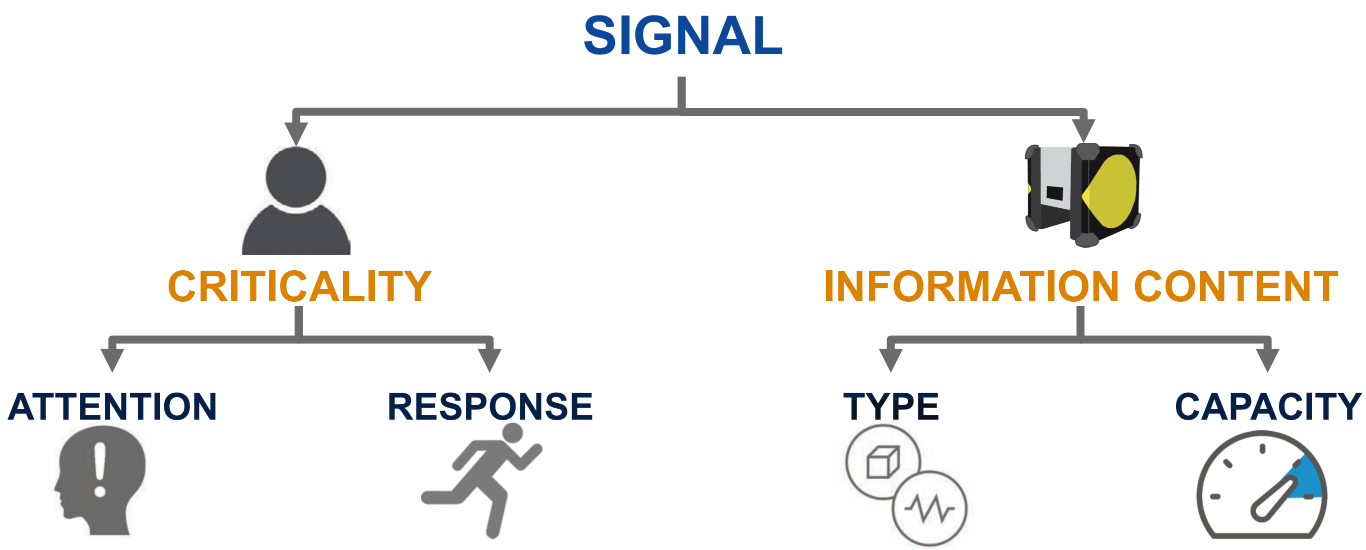
- When humans and robots must co-exist in the same space, there is often a need for spatial negotiation
- Cannot always rely on pre-defined rules (e.g., "right of way") due to ambiguity and uncertainty
- Signaling (lights, movement, sound, etc) is an effective manner to communicate intent and elicit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



Signaling for human-robot interaction

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.)



E. Cha, Y. Kim, T. Fong, and M. Mataric (2018) **“A survey of non-verbal signaling methods for non-humanoid robots”** Foundation & Trends in Robotics 6(4).

Astrobee free-flying space robot

Specs

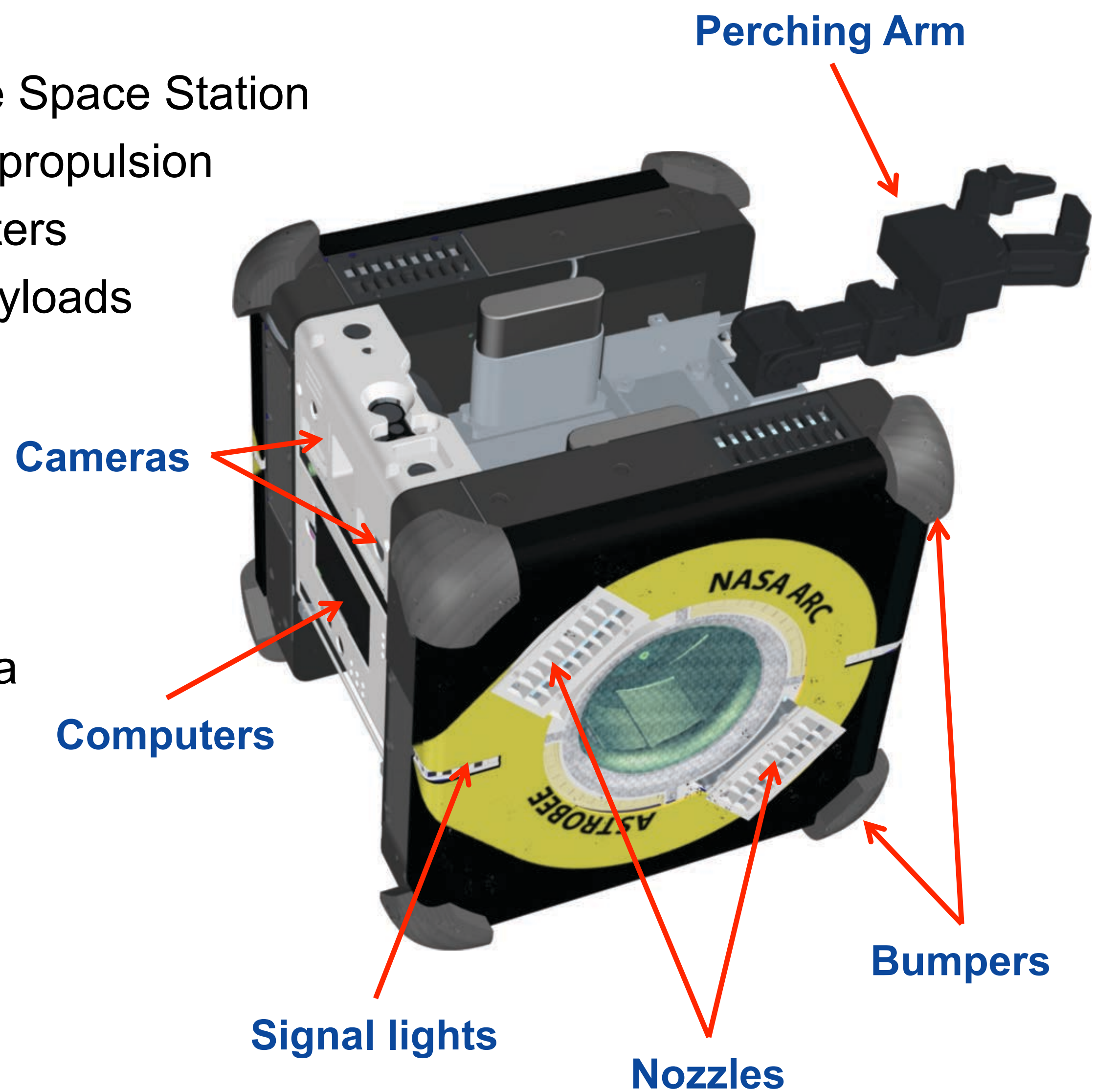
- Free flying robot inside the Space Station
- All electric with fan-based propulsion
- Three smartphone computers
- Expansion port for new payloads
- Open-source software
- 30x30x30 cm, 8 kg

Uses

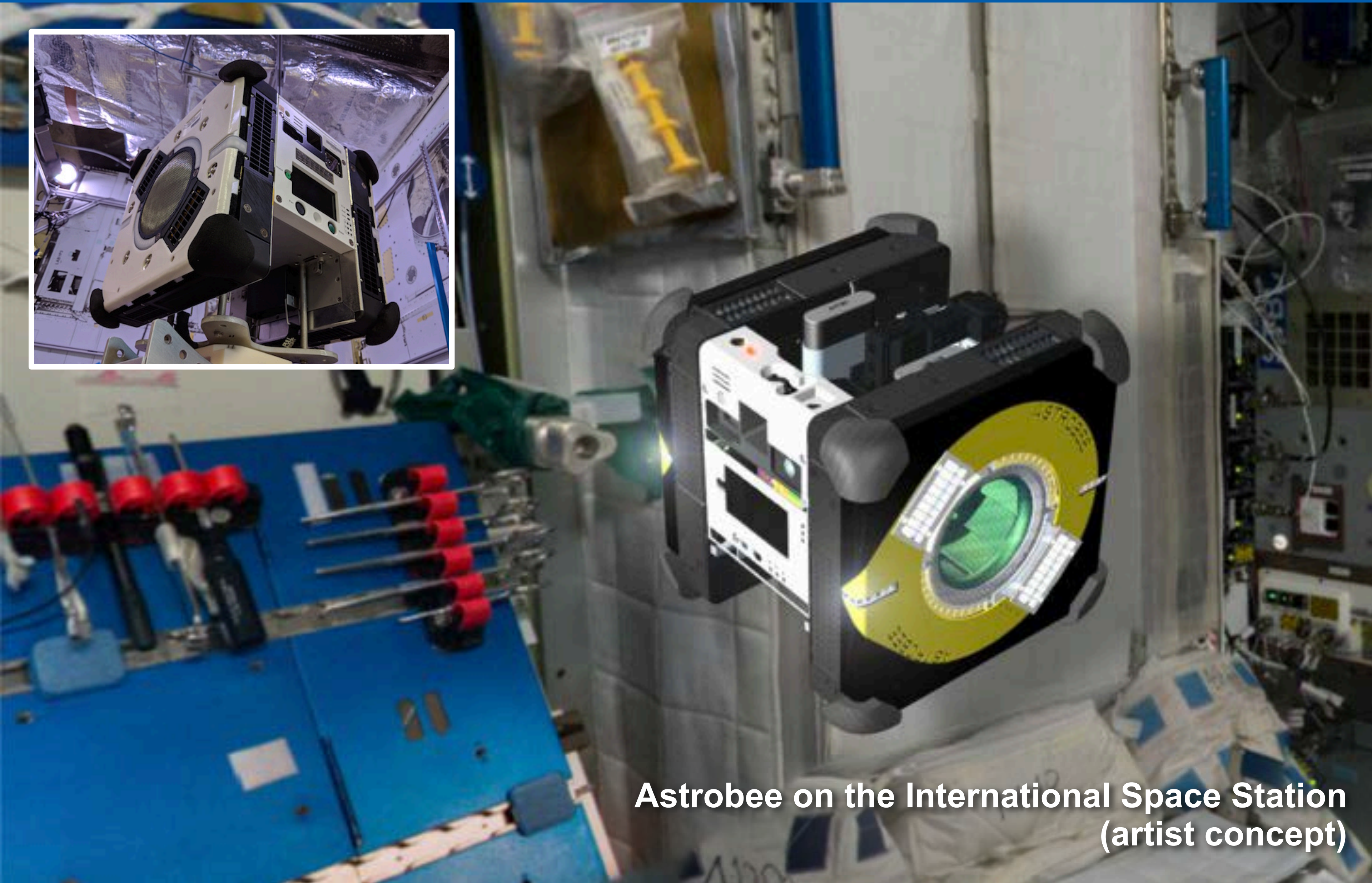
- Mobile sensor
- Remotely operated camera
- Zero-G robotic research

Autonomy

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

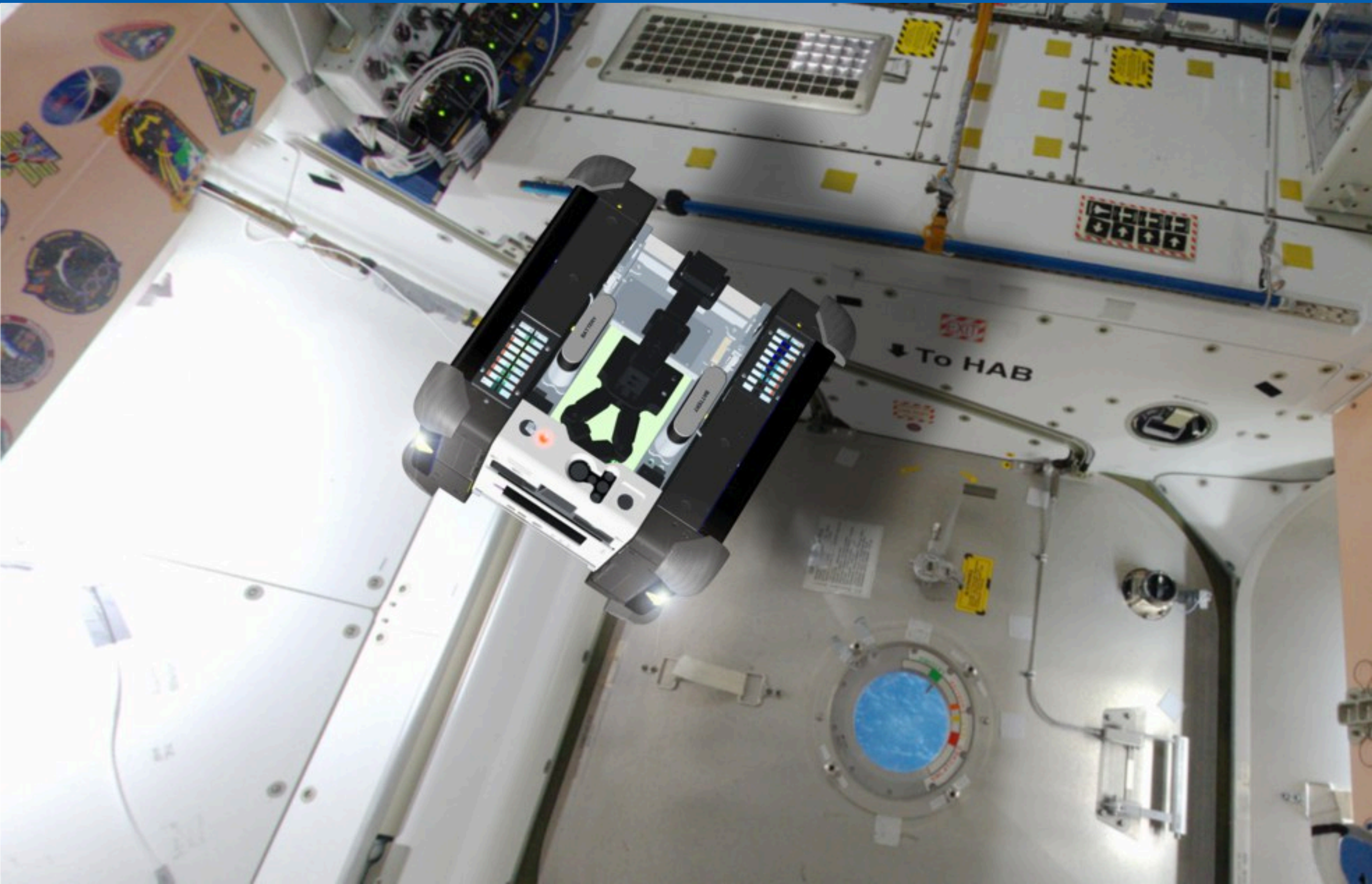


Astrobee – free-flying space robot



Astrobee on the International Space Station
(artist concept)

Astrobee on the Space Station (concept)

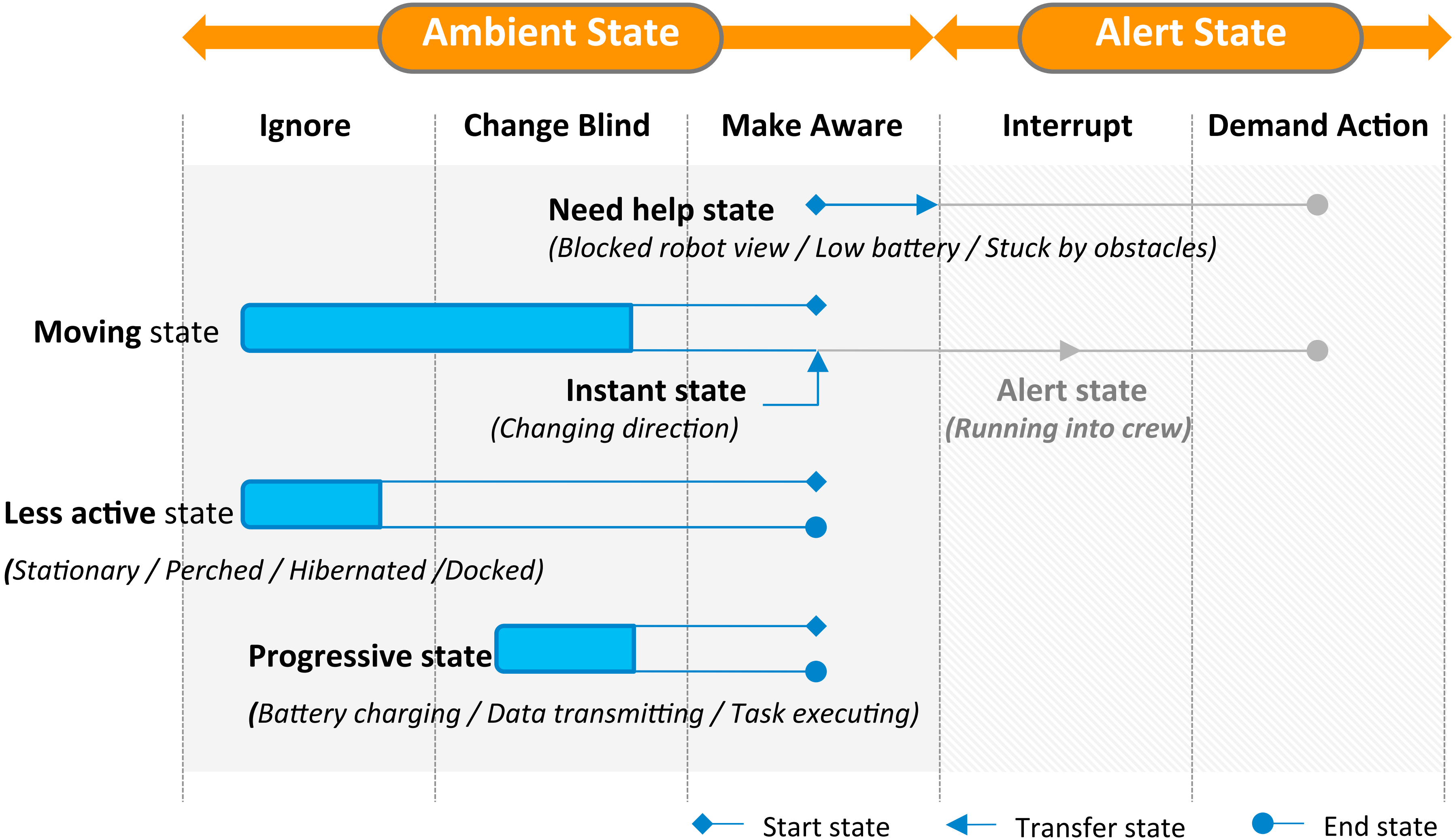


Astrobee on the Space Station (concept)

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)

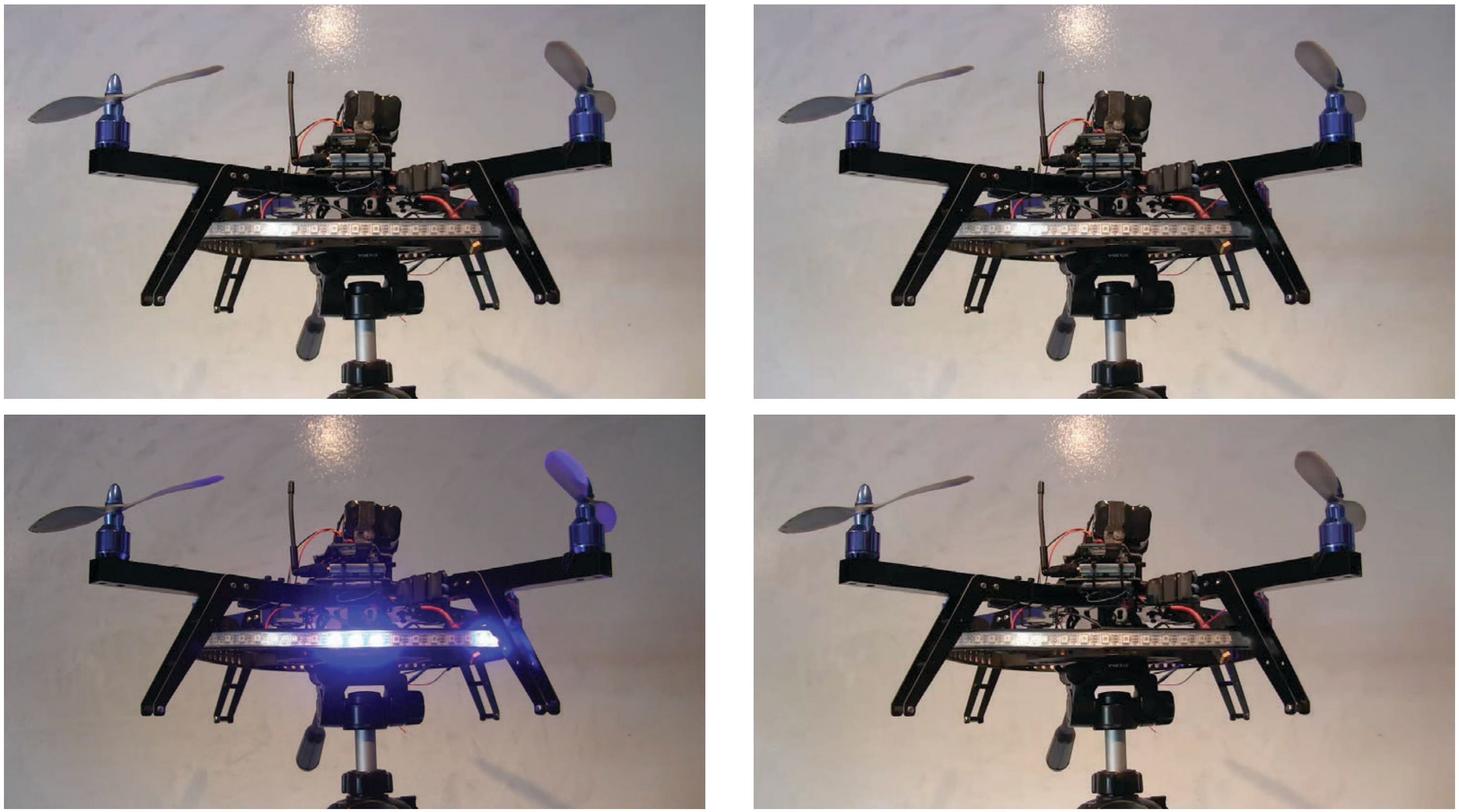
Notification levels



Light signaling for free-flying robots

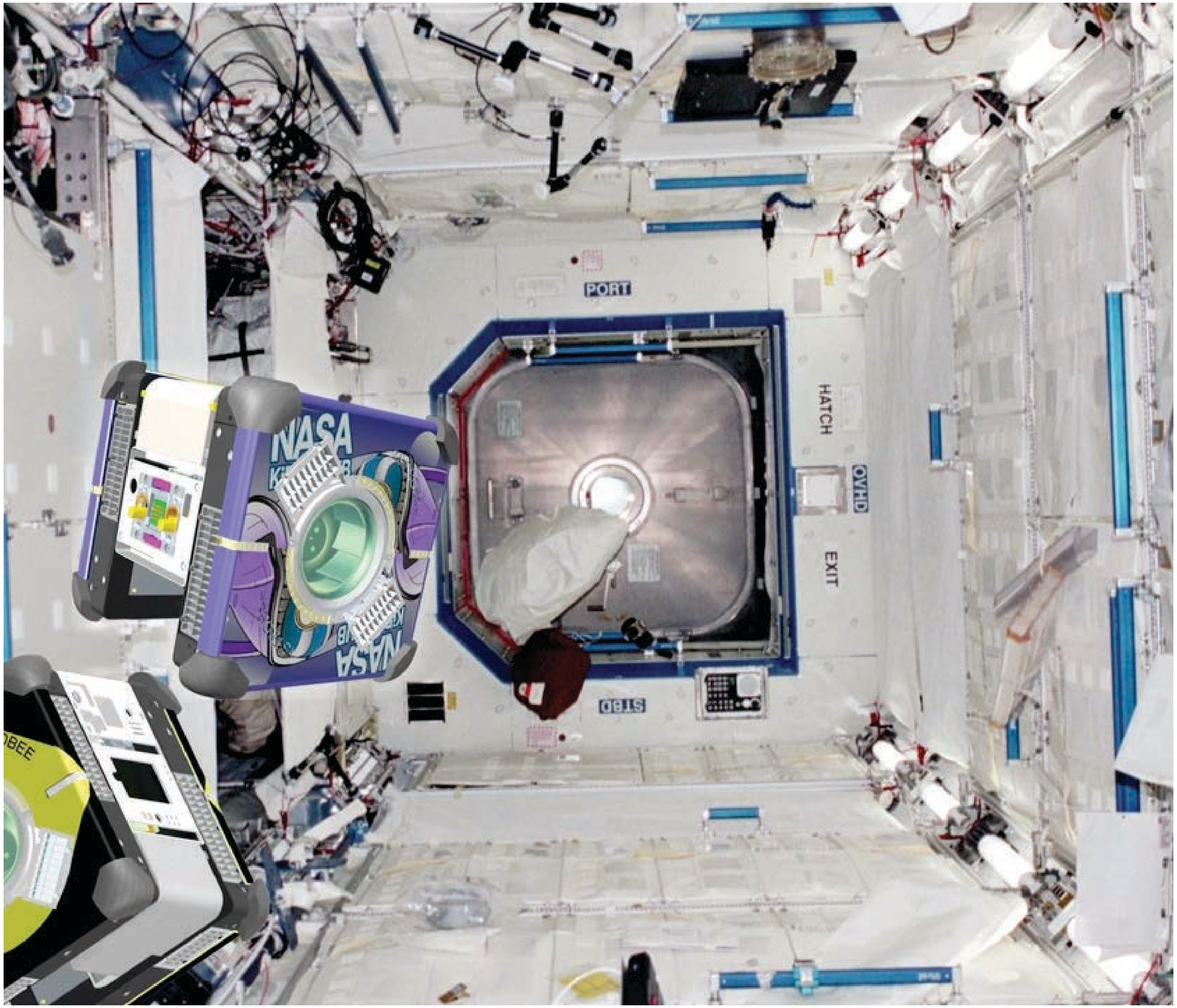
beacon | blinker

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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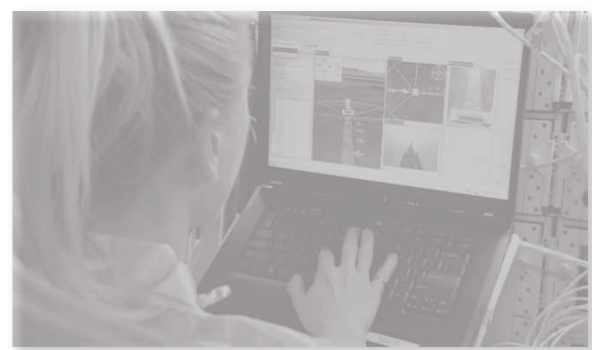
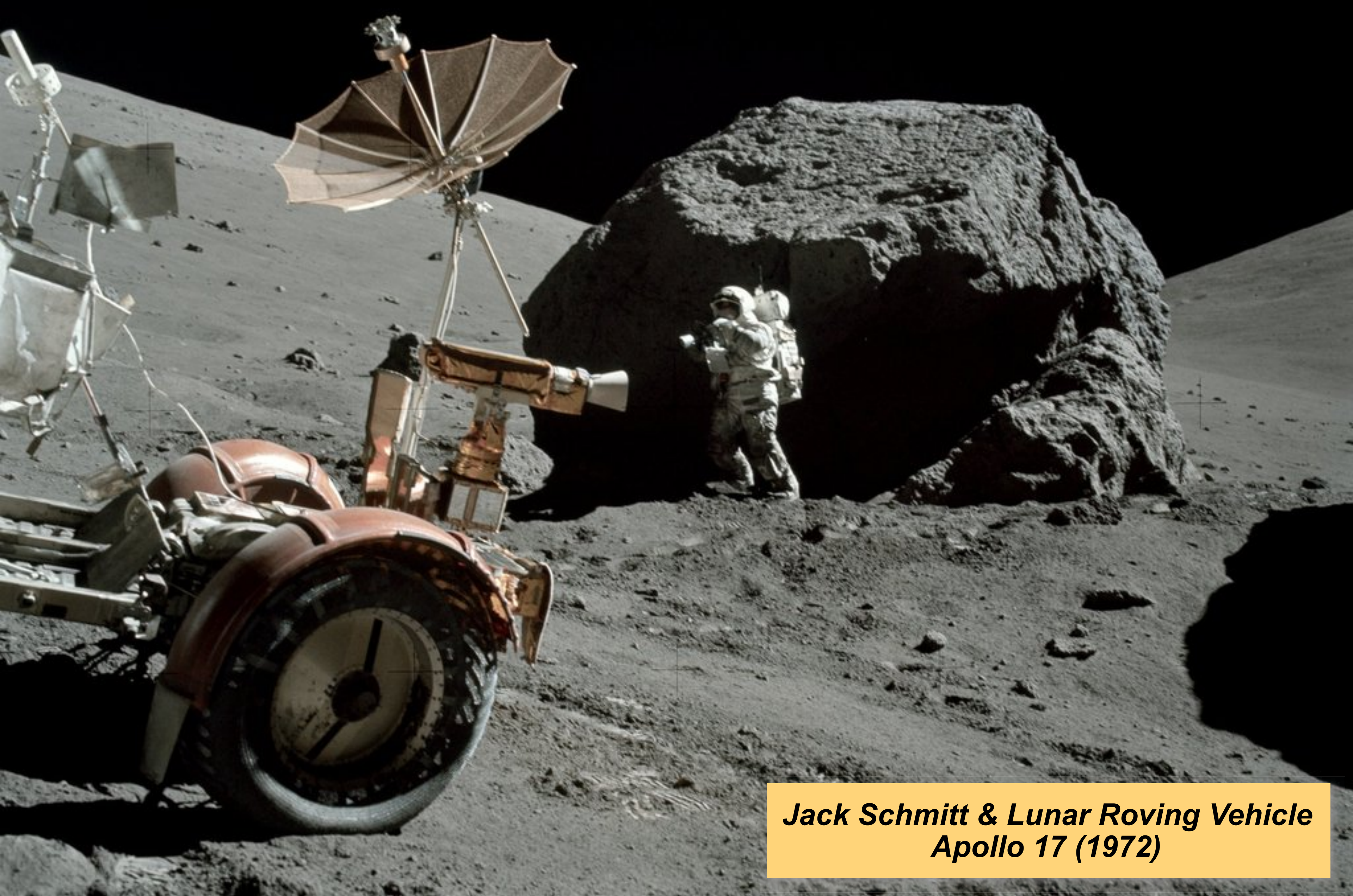
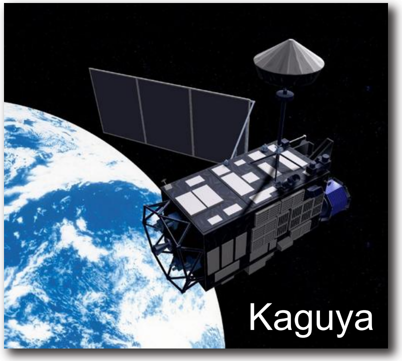


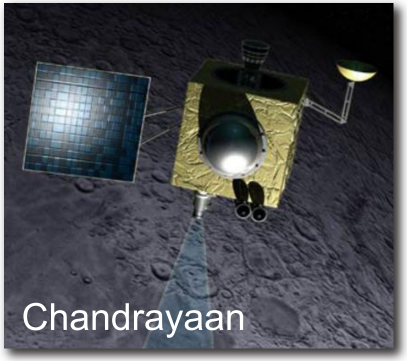
Human planetary exploration



Jack Schmitt & Lunar Roving Vehicle
Apollo 17 (1972)

What's changed since Apollo?


Kaguya


Chandrayaan

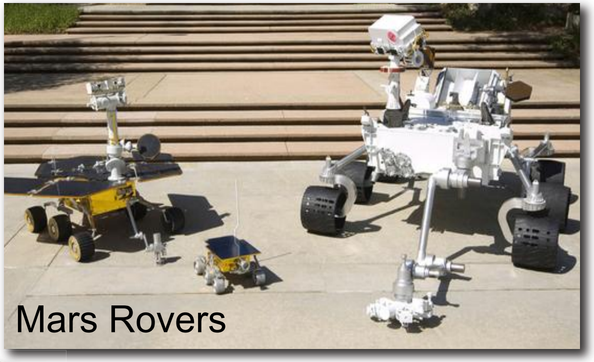

LRO


Space Station


Phoenix


Robonaut 2


LCROSS


Mars Rovers


ATHLETE, K10, Chariot

Robots for human exploration

Robots **before** crew

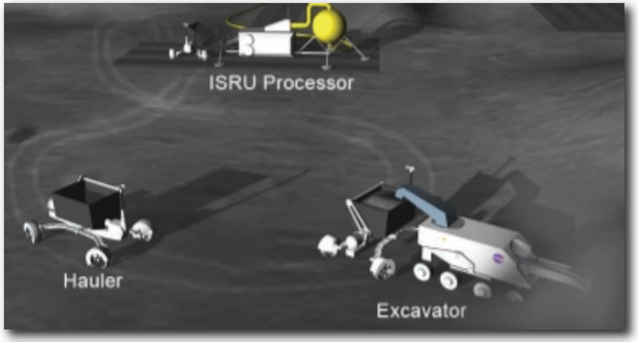
- Prepare for subsequent human mission
- Scouting, prospecting, etc.
- Site preparation, equipment deployment, infrastructure setup, etc.

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.



T. Fong, M. Deans, and M. Bualat (2013). **"Robotics for human exploration"**. IFR International Symposium on Robotics

Robotic Follow-up Project (2009)

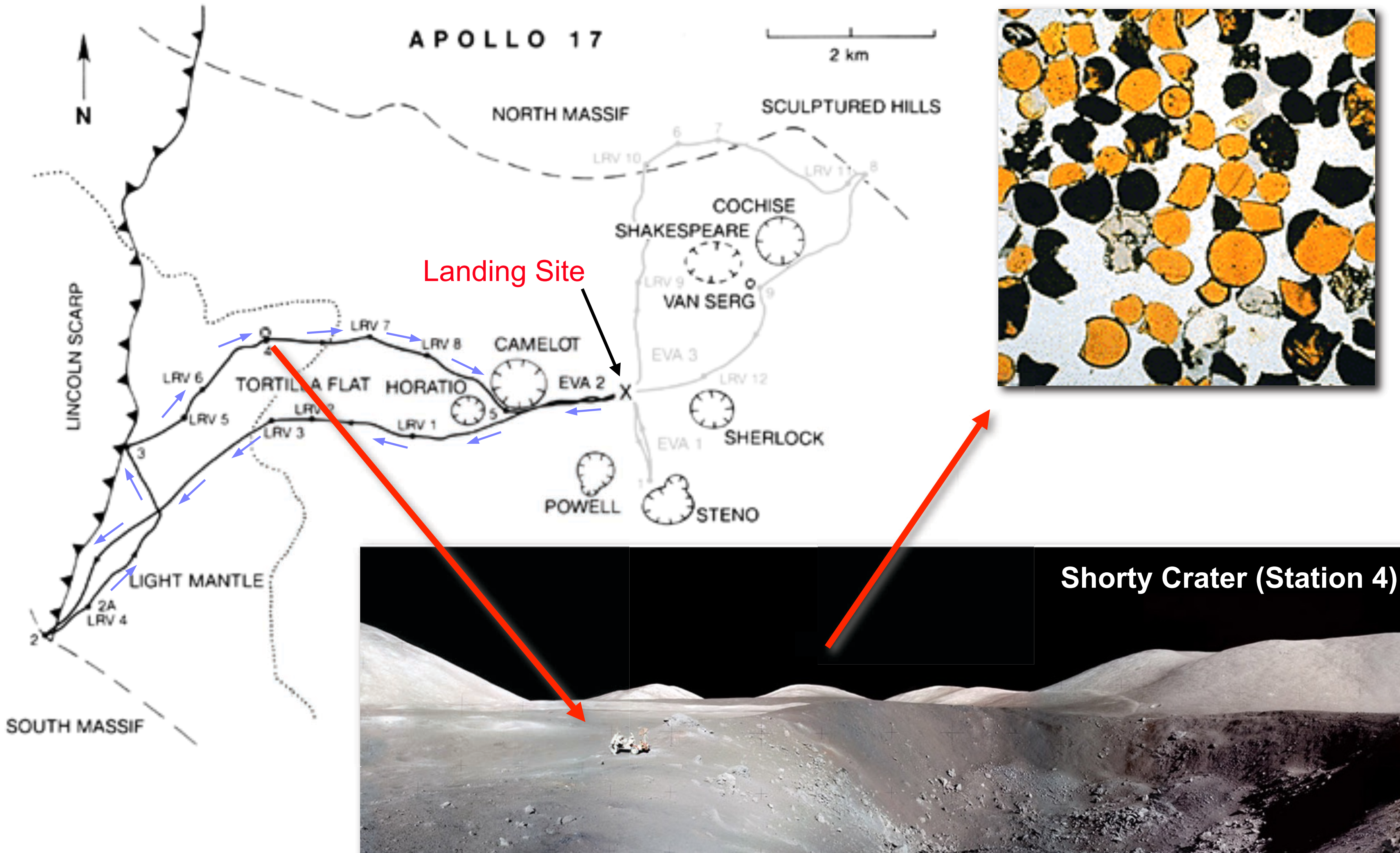
An exploration problem

- 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 **subsequent** 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)

Crew mission

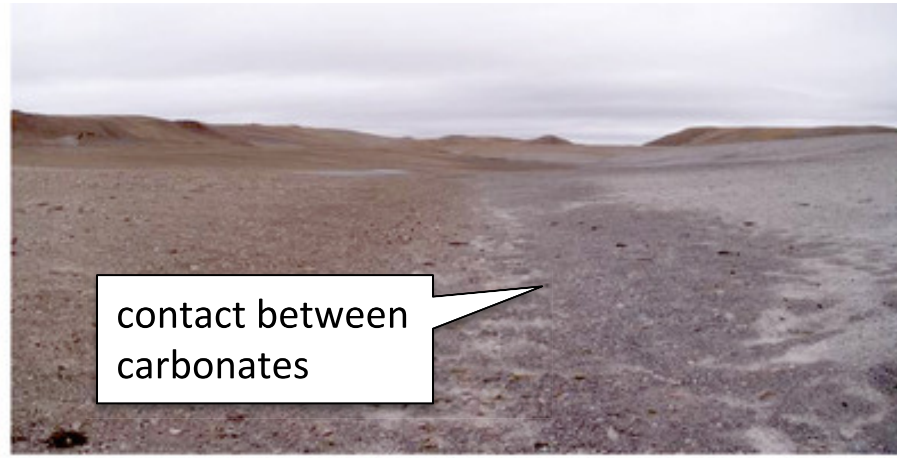
Geologic Mapping

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

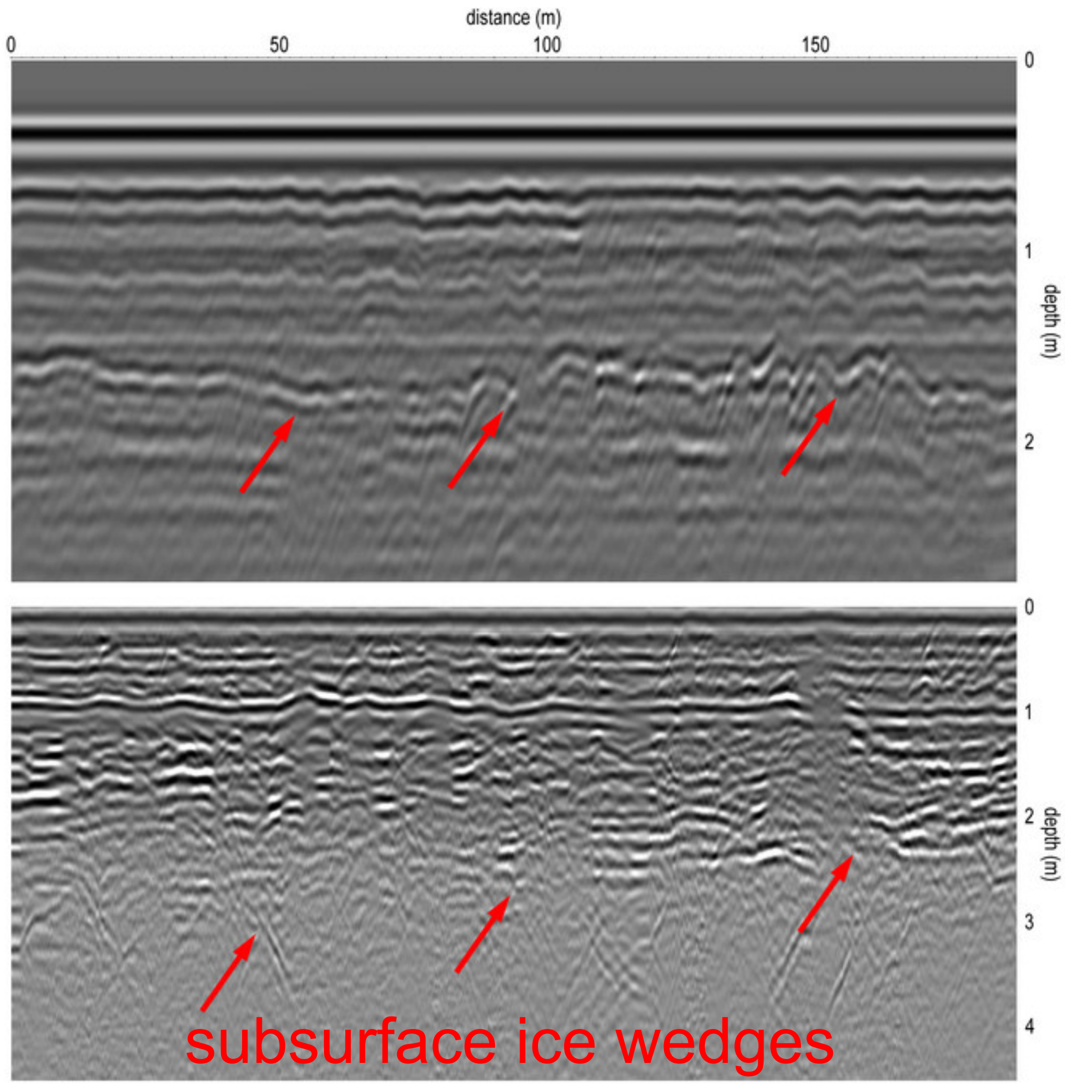
Geophysical Survey

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

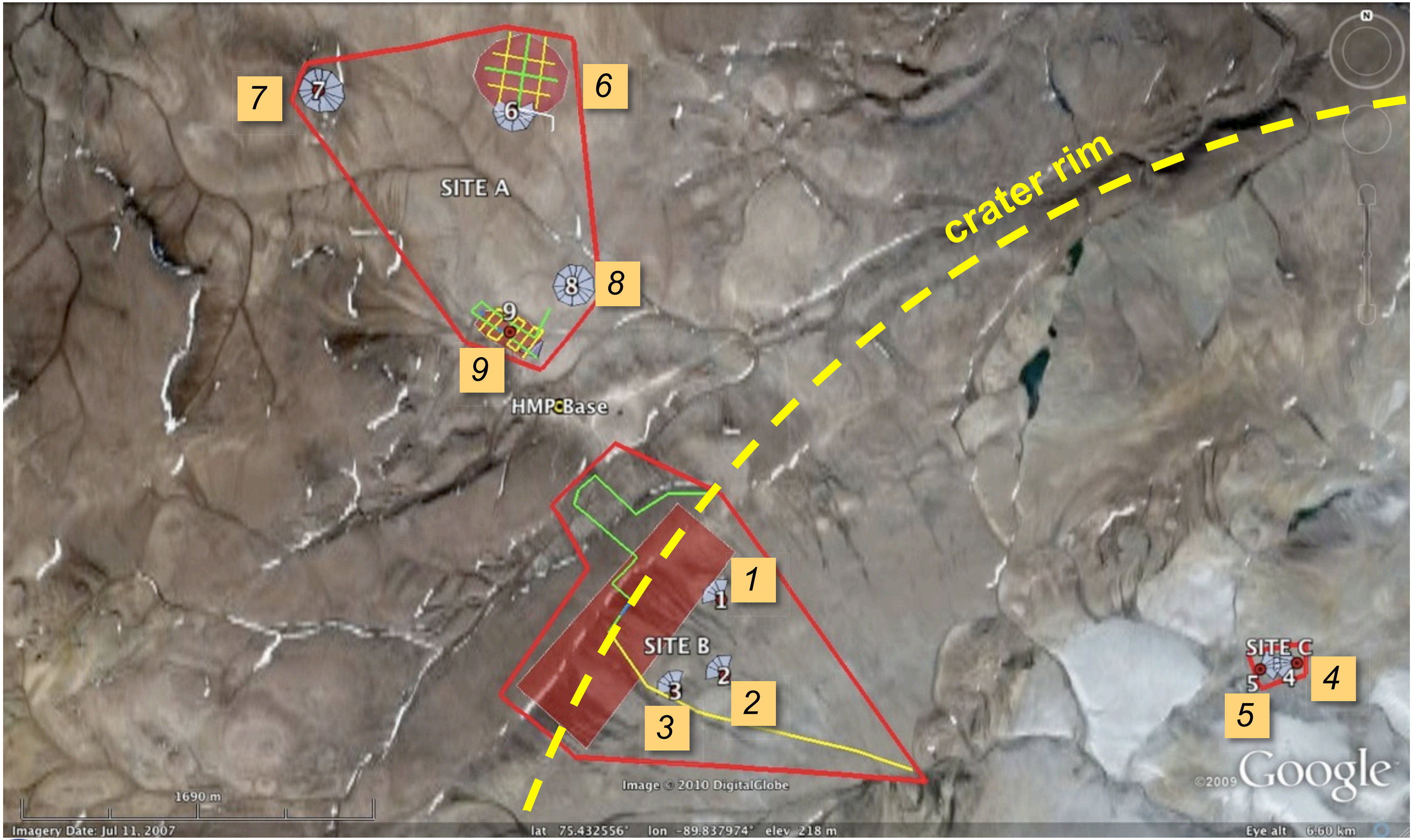
Geologic mapping results



Geophysical survey results



Robotic follow-up plan

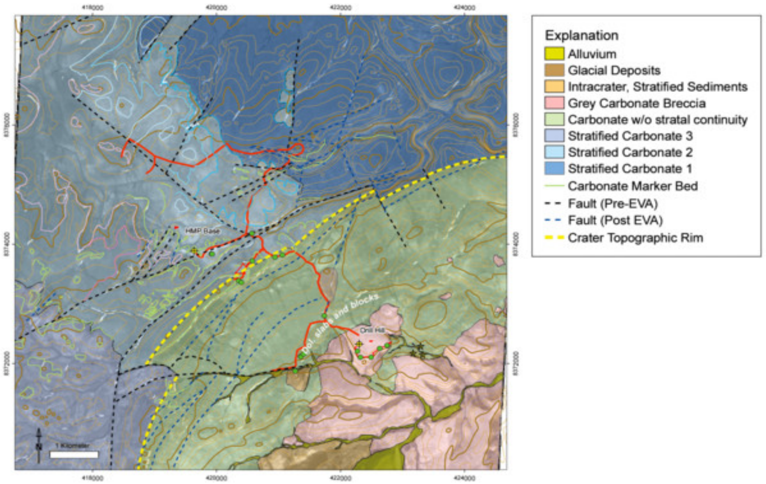



NASA

Robotic follow-up results

Geologic Mapping

- **Verified the geologic map** in multiple locations (revisited and confirmed geologic units)
- **Amended the geologic map** in multiple locations (added detail to long-range crew observations)



Geophysical Survey

- **Detail study of "polygons"** (correlated surface & subsurface features identified by crew)
- **Measured average depth** of subsurface ice layer (refined observations from crew)

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

Research @ NASA Ames

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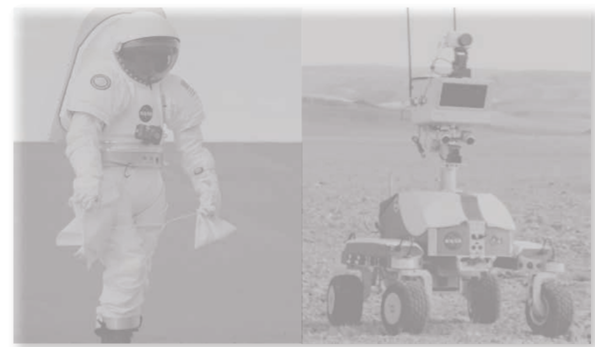

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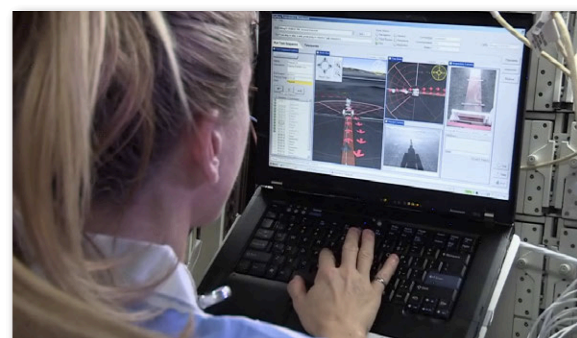


Human-robot collaboration

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.

Why Autonomy is Hard*

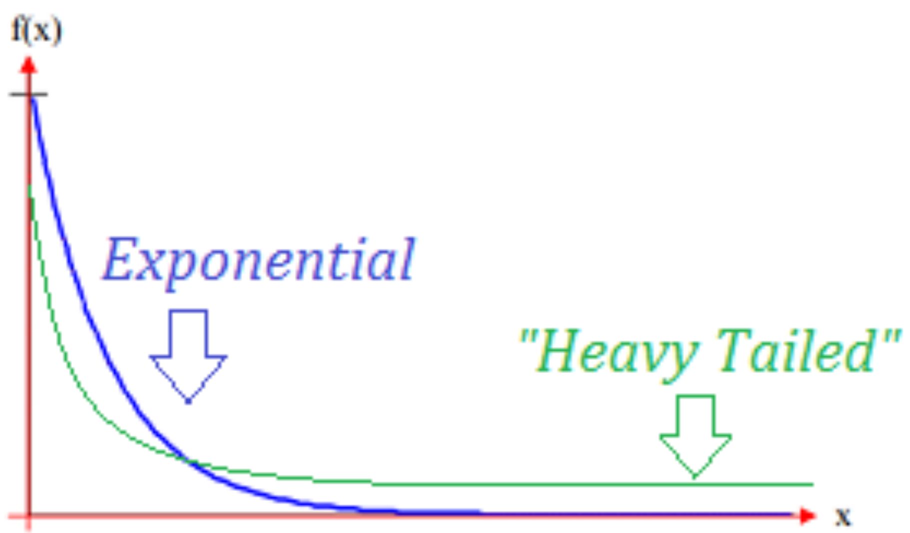
The real world is highly uncertain and changing

- "There are **known knowns**. There are things we know that we know. There are **known unknowns**. That is to say, there are things that we now know we don't know. But there are also **unknown unknowns**. There are things we do not know we don't know."

  – Donald Rumsfeld, 2002

The real world is a heavy-tailed distribution

- High probability of encountering **unexpected events** when operating for a long time or when performing many activities



All models are approximations

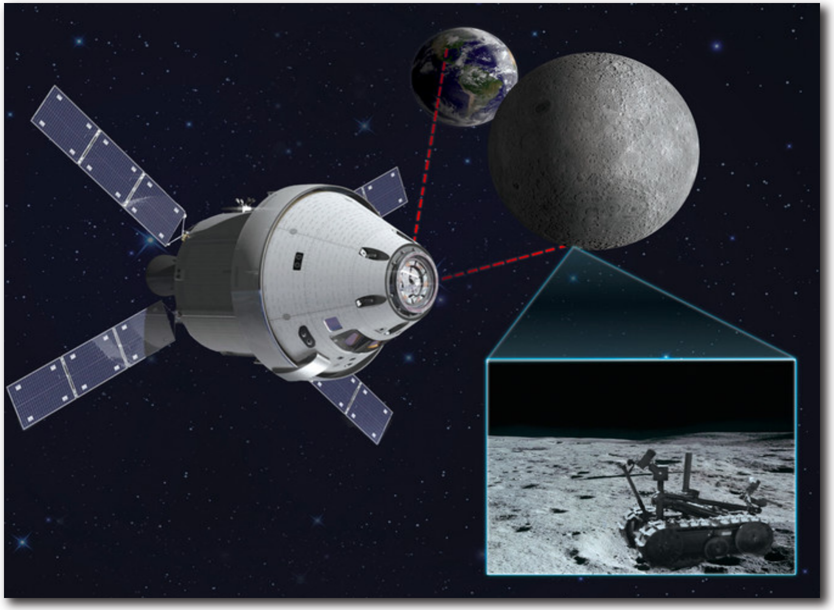
- Modeling unknowns and uncertainty is really hard
- Computation is (not yet!) instantaneous and infinite

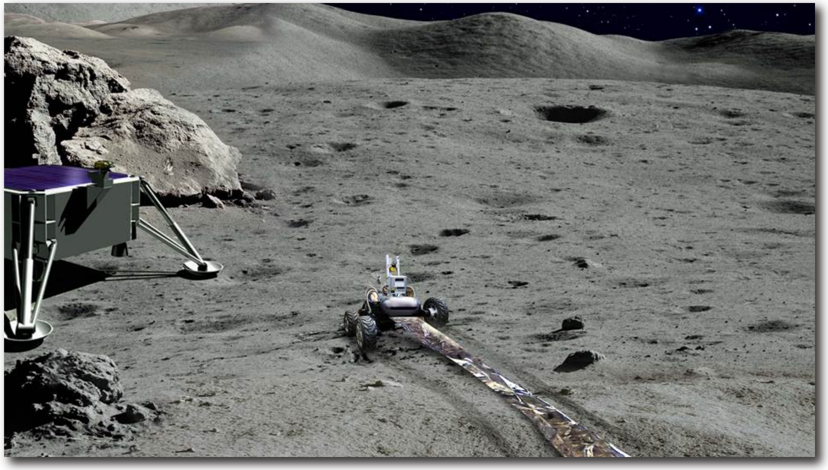
** Credit: Reid Simmons*

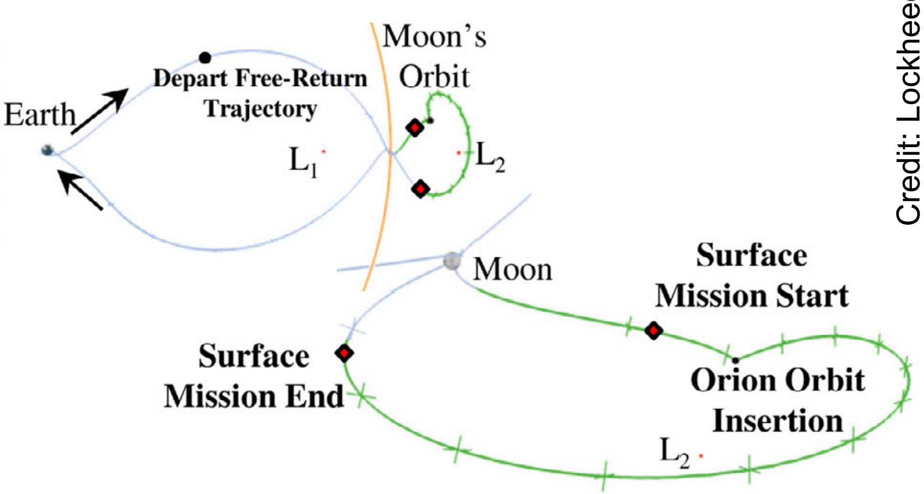
Lunar Mission Concept

Orion at Earth-Moon L2 Lagrange

- Astronaut remotely operates lunar rover from orbiting spacecraft – ***"Avatar" in real-life …***
- Spacecraft orbiting 60,000 km beyond lunar farside
- High-bandwidth, low-latency data communication between spacecraft and surface robot







Credit: Lockheed Martin / LUNAR

Lunar Mission Simulation

“Surface Telerobotics” Project

- Simulation of the “Orion at Earth-Moon L2 Lagrange” concept
- Astronauts in the International Space Station (ISS)
- K10 planetary rover at NASA Ames
- Data comm via satellite relay with short delay (**750 msec round-trip**)
- Asynchronous bandwidth (**3 Kbps downlink, 800 Kbps uplink**)

ISS Expedition 36 testing

June 17, 2013 – **C. Cassidy**, survey

July 26, 2013 – **L. Parmitano**, deploy

Aug 20, 2013 – **K. Nyberg**, inspect

SURVEY

DEPLOY

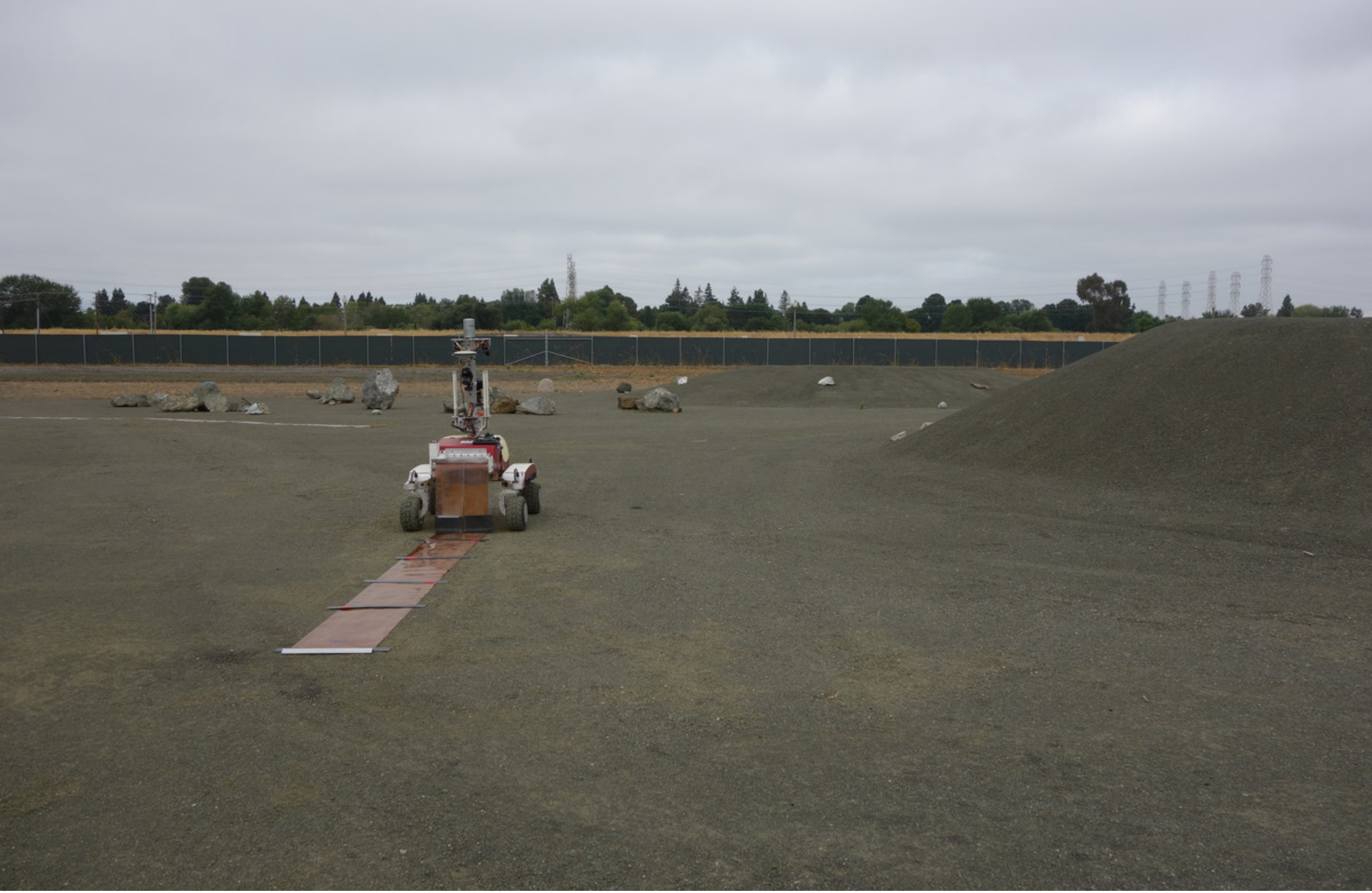
INSPECT

Astronaut in space / Robot on Earth

Chris Cassidy remotely operates K10 from the ISS to perform site survey (2013-06-17)

K10 performing surface survey

Luca Parmitano works with K10 to deploy simulated polymide antenna (2013-07-26)



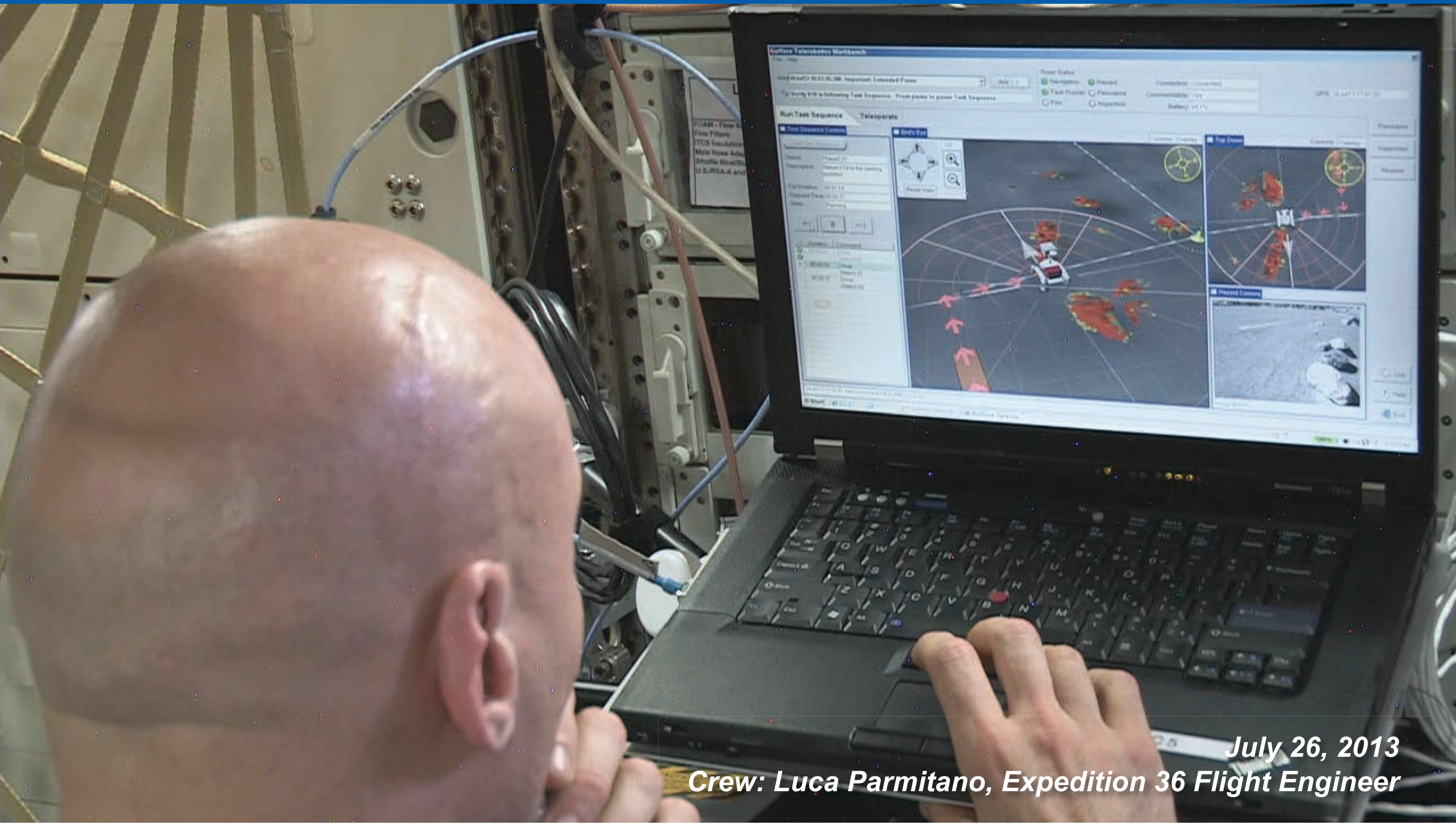
K10 deploying simulated polymide antenna

Deployed simulated polymide antenna (three "arms")

Karen Nyberg works with K10 to document deployed simulated antenna (2013-08-20)

K10 documenting simulated polymide antenna

Astronaut remotely helping a space robot



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

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** *(ideally should be as high as possible…)*

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

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

Self-driving cars at NASA Ames

Public/private partnerships

- **Google** (2014-15): collaborative testing of sensors and vehicles
- **Nissan** (2014-19): cooperative software development

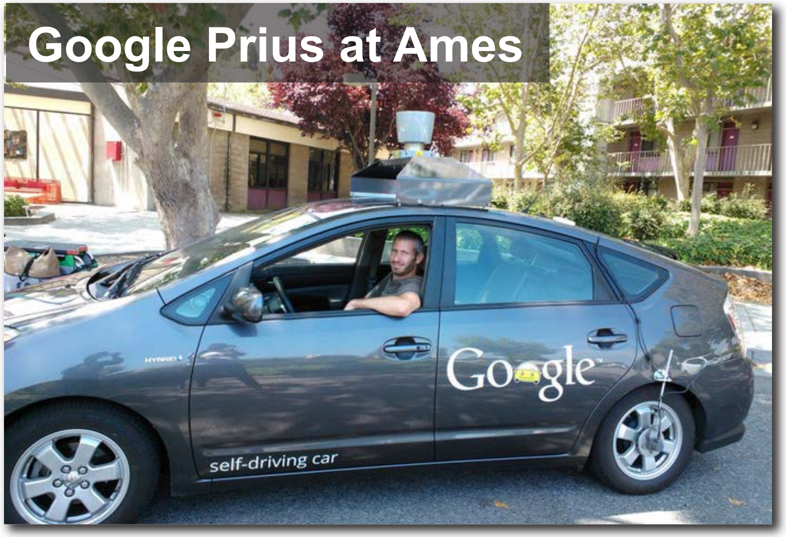
NASA interest

- 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

Nissan Leaf at Ames



Google Prius at Ames

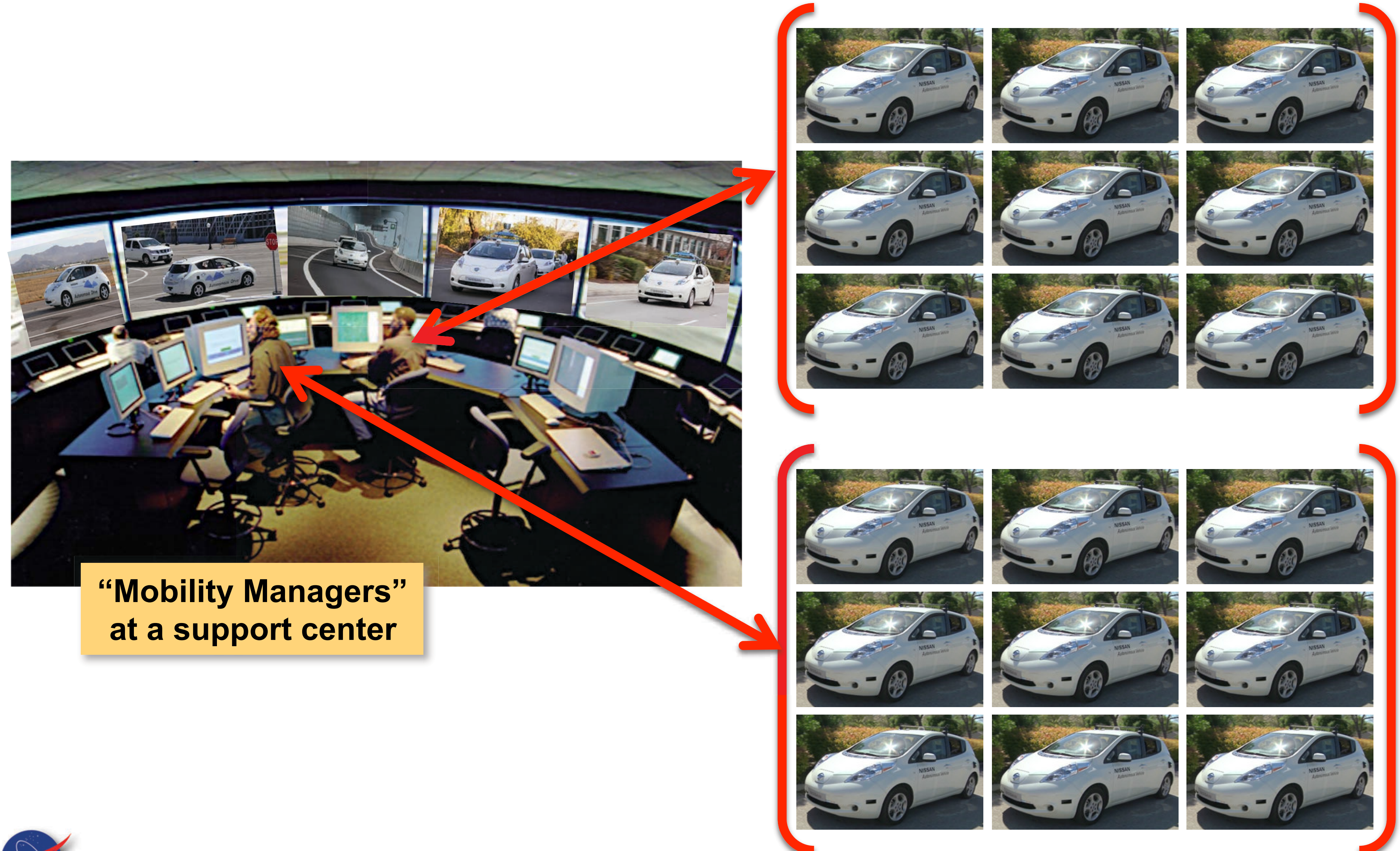
Imperfect vehicle autonomy

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)

Humans remotely helping self-driving cars



Human remotely helping a self-driving car

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

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?

Human-robot teaming

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