Jet Propulsion Laboratory
California Institute of Technology

JPL Autonomy Research and Applications

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HF DoD TAG

Special Session: Autonomous Systems

NASA LaRC

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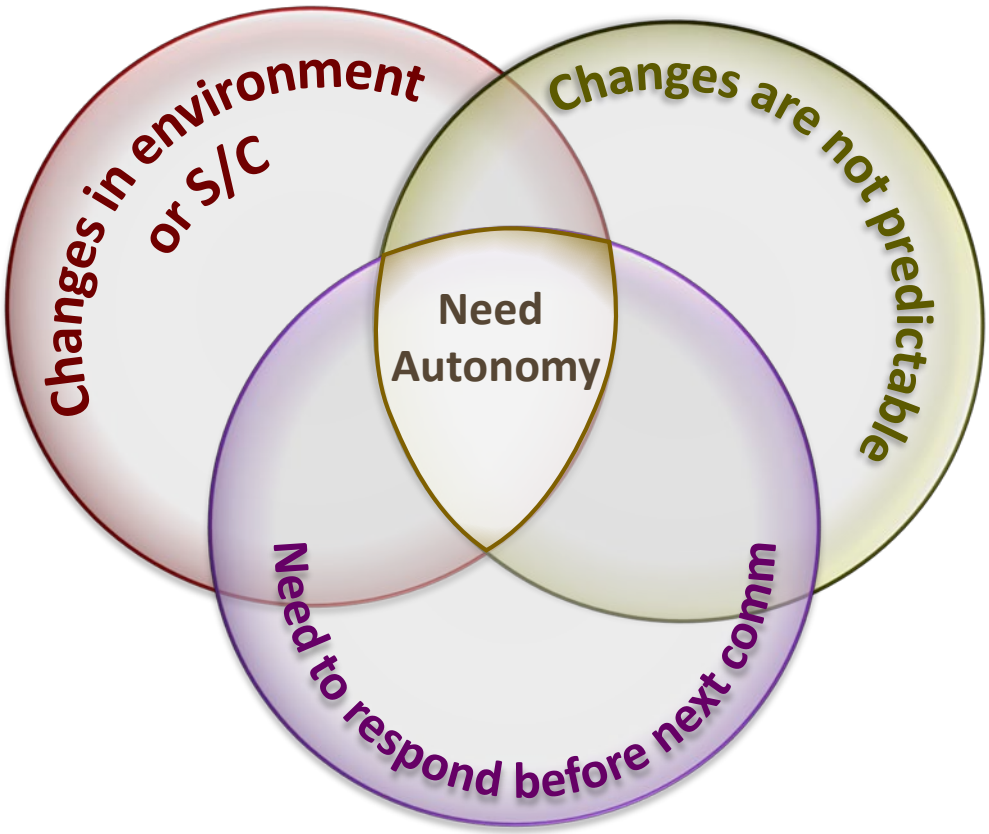
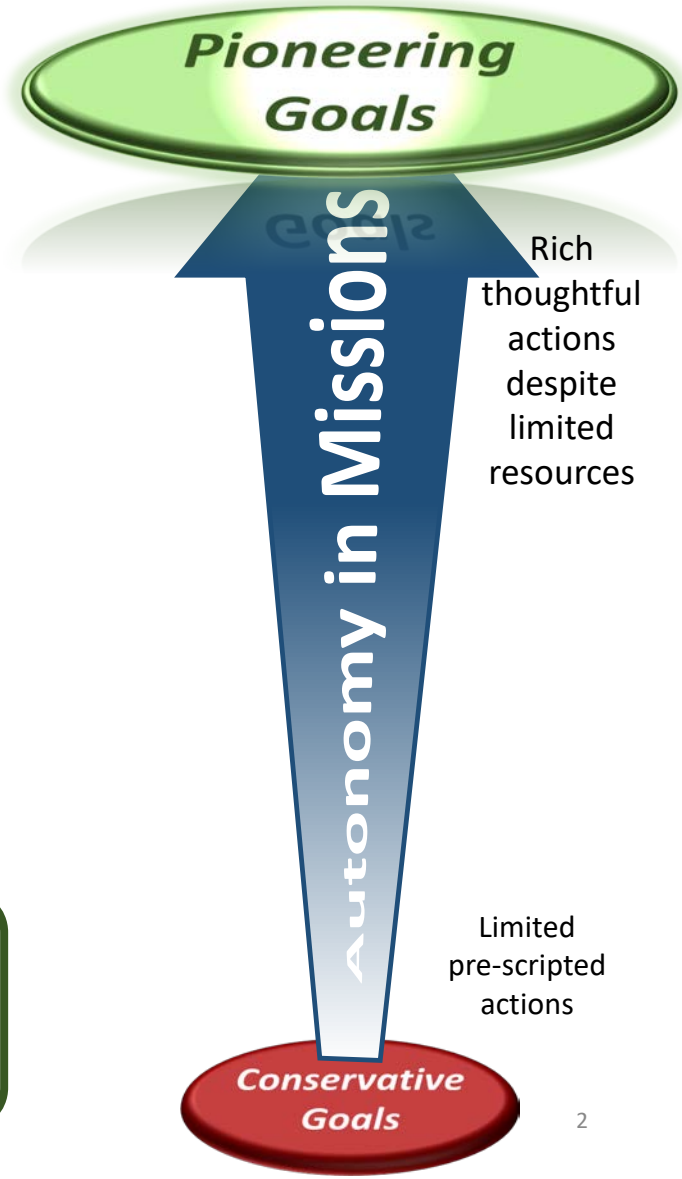
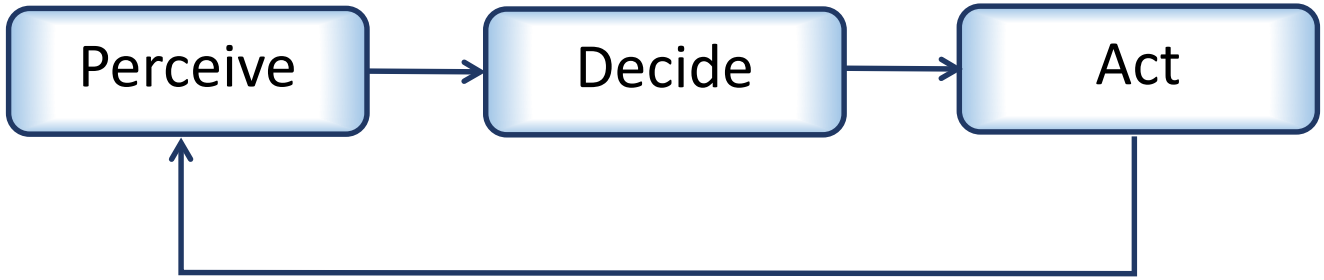
The Need for Autonomy





Autonomy enables pioneering missions:
- Explore new destinations and increase science yield, robustness, operability

What is Autonomy?



Autonomy: *To make decisions and take actions, in the presence of uncertainty, to execute the mission and respond to internal and external changes without human intervention.*

Hardware
- *Sensing and perception*
- *Computing*
- *System architecture*

Software
- *Autonomy algorithms*
- *Autonomy architecture and infrastructure*

Systems Engineering
- *System design*
- *Verification and validation*
- *Operations*

Autonomy Taxonomy

Autonomy viewed as a spectrum:

Less Autonomy	*More Autonomy*
Limited to a few functions	*All functions are autonomous*
Functions are optional	*Function are critical*
Limited decision options	*Wide decision space*
Environment well-characterized and understood	*Unknown/unpredictable environment*
Models manually updated	*Learns and adapts*
Operators closely supervise execution	*Lights out operations*

Time-based sequences

Conditional decision-making

Onboard activity planning

Reasoning in large decision space

Learns from past experience

Unplanned situations halts execution and require human input

Onboard state awareness of system and environment

Responds to unplanned situations without human input

Design for Autonomy

Advanced avionics

- Orders of magnitude improvement in compute capability; process large, high volume, high data rate instruments and sensors; reliable, diagnosable computing and buses

Smart Sensing

- Filter out noise; compensate for errors; reliable, self-calibration, self-testing, self-diagnosis, power-efficient, high-throughput, diverse, small and abundant engineering sensors

Function-level Autonomy

- Algorithms that make certain functions autonomous such as autonomous cruise, proximity ops, EDL, mobility, manipulation, image recognition and science decision making

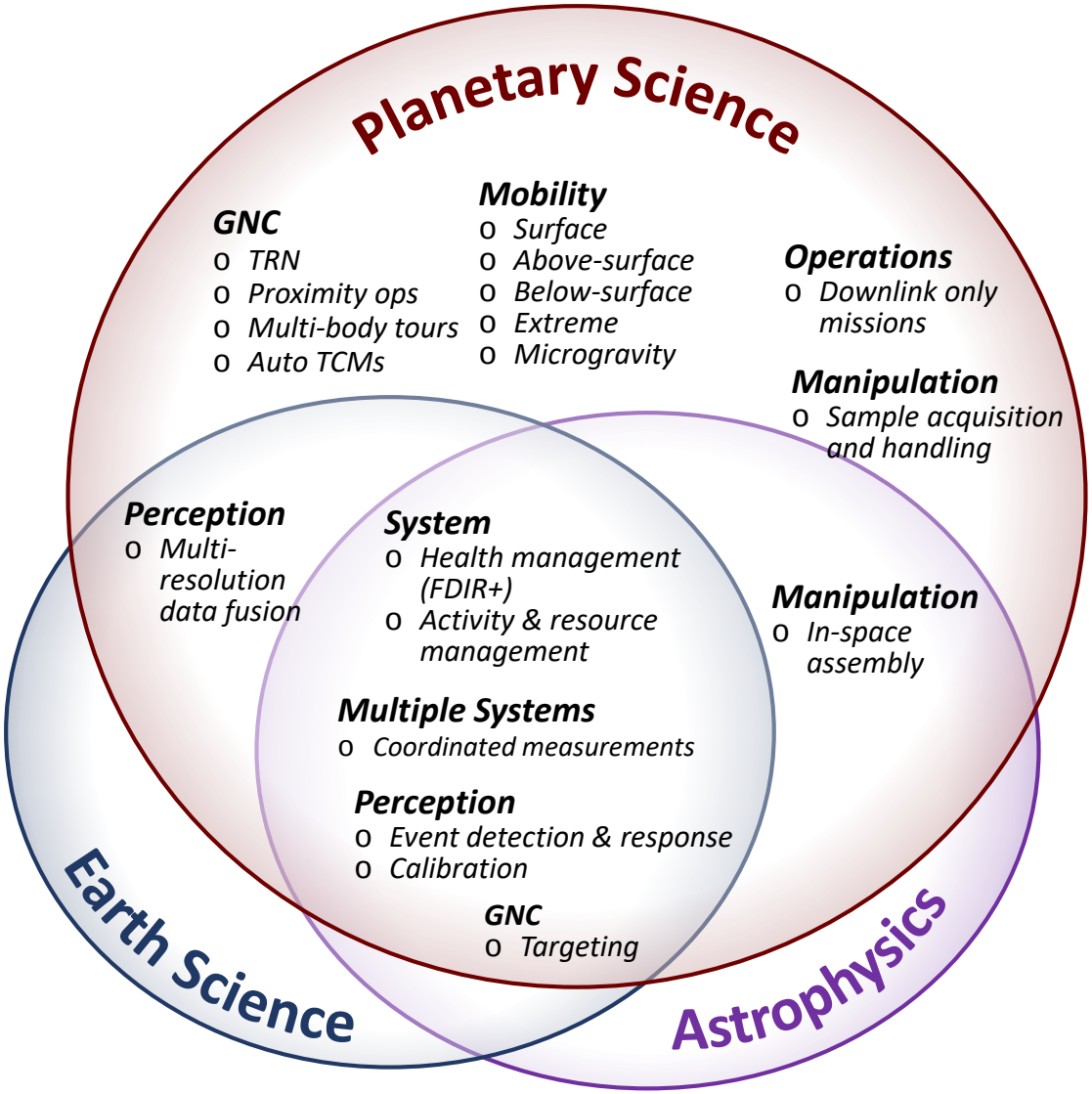
System-level Autonomy

- System infrastructure and architecture for health, activity, and resource management

Systems Engineering / Operations

- Systems engineering, V&V, and operations training

Autonomy is Integral to All Missions



Entry, Descent and Landing

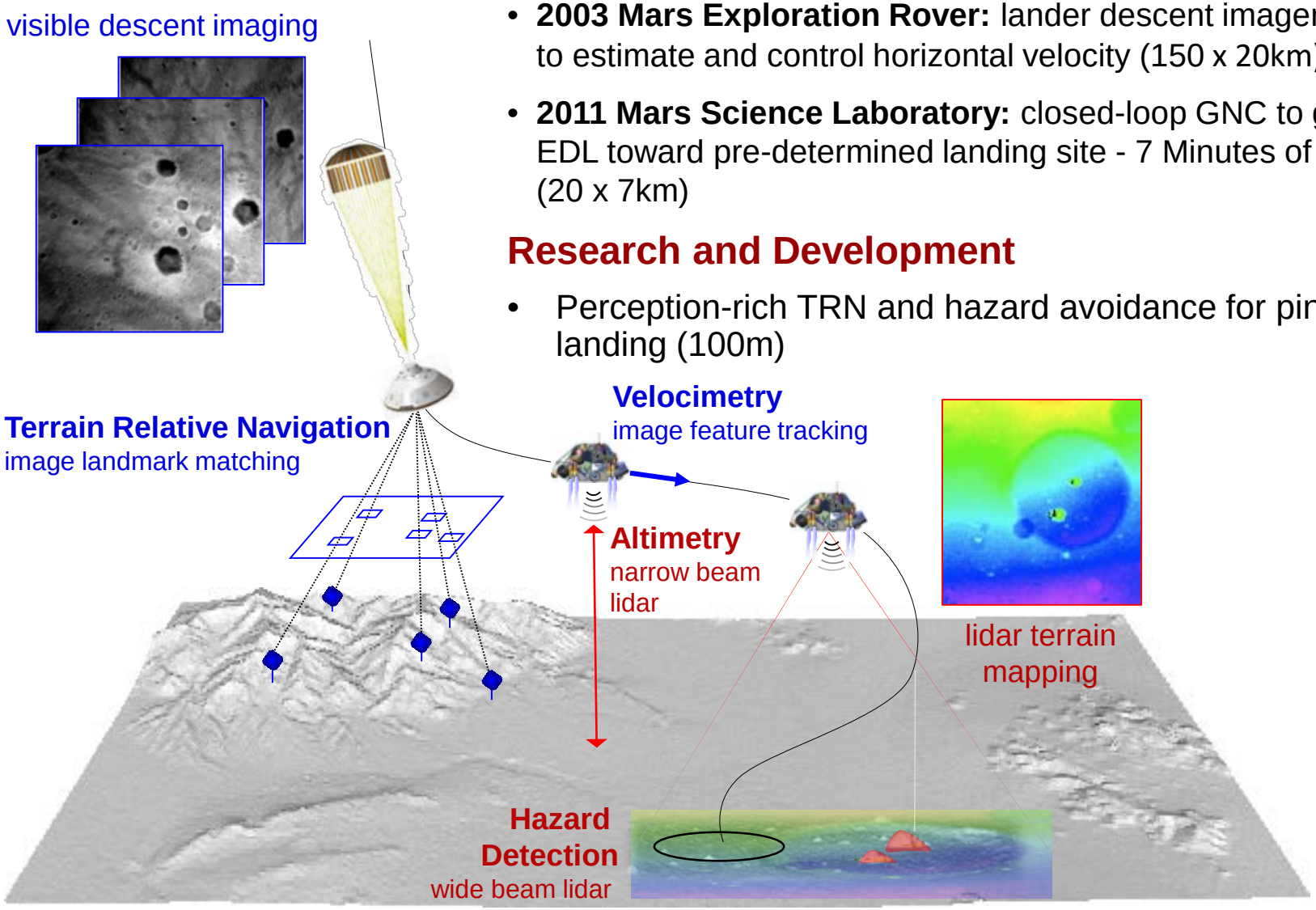
Terrain Relative Navigation and Hazard Avoidance

Flight Deployed

- **2003 Mars Exploration Rover:** lander descent imagery used to estimate and control horizontal velocity (150 x 20km)
- **2011 Mars Science Laboratory:** closed-loop GNC to guide EDL toward pre-determined landing site - 7 Minutes of Terror (20 x 7km)

Research and Development

- Perception-rich TRN and hazard avoidance for pin-point landing (100m)



Proximity Operations

Flight Deployed

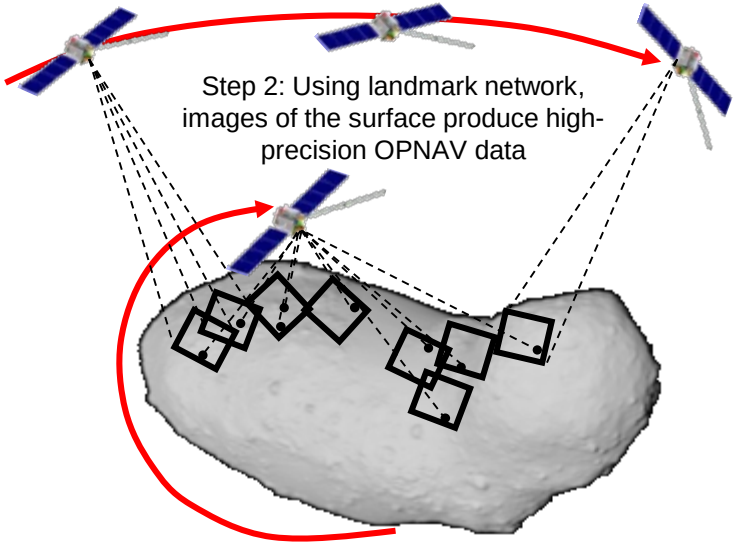
- **1998 Deep Space One:** autonomous navigation system (AutoNav), later used on three other spacecraft for four different missions. Primary use has been on comet missions to track comets during flybys, and impact one comet (DI)
- **2001 NEAR:** landmark-based optical navigation of and touchdown on small bodies
- **2011+ Multiple (DAWN, Rosetta):** stereo-photoclinometry (SPC) for shape modeling

Research and Development

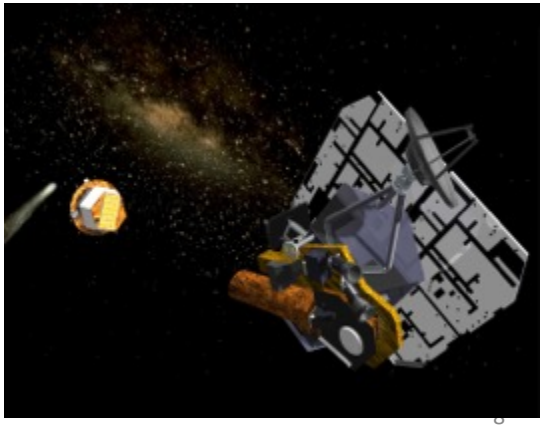
- Maneuvering around small bodies using perception-rich navigation for hovering, landing, touch-and-go (TAG) sampling, multiple flybys and fly-around

Field-testing sensor hardware

Step 1: Survey from high orbit to develop a set of landmark models and control network.



Step 3: Combine data from individual images in a nav filter with other data (e.g. radiometric or LIDAR) to estimate S/C position



Deep Impact

Surface Mobility

Mars Rover Navigation

Autonomy TIM

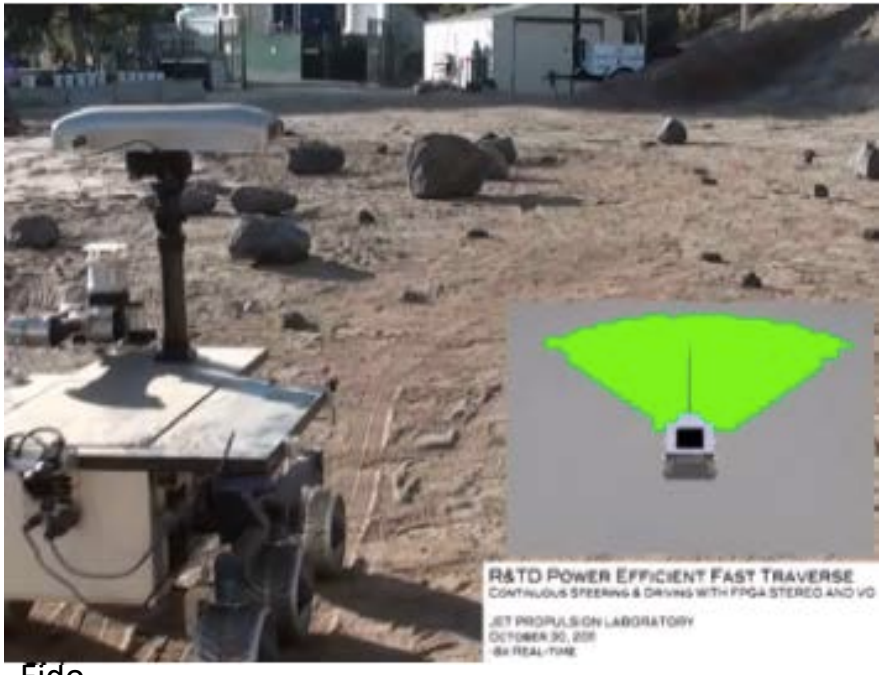
Flight Deployed

- **1996 Mars Pathfinder:** obstacle avoidance with structured light
- **2003 Mars Exploration Rover:** obstacle avoidance with stereo vision; pose estimation and slip detection with visual odometry; goal tracking
- **2011 Mars Science Laboratory:** enhanced obstacle avoidance, visual odometry and goal tracking

Research and Development

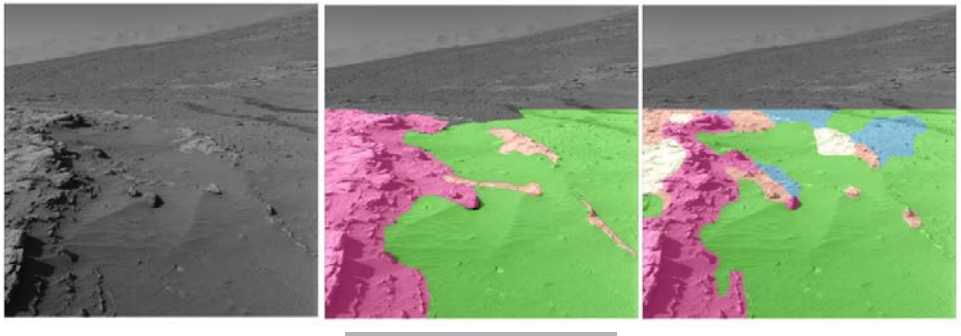
- Enhanced hazard detection, traversability analysis and motion planning for Mars 2020 and beyond

Athena



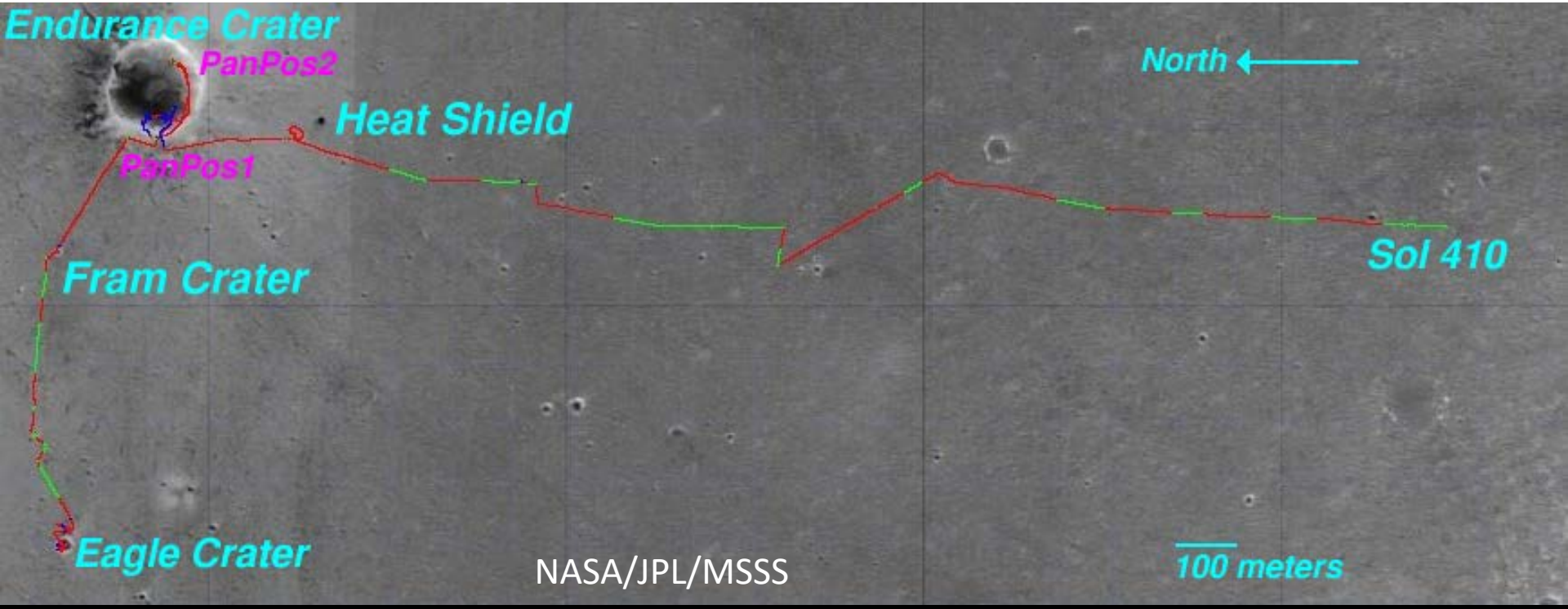
Fido

Raw Navcam | Human | Terrain classifier



Terrain Classification

Opportunity Traverse (through Sol 410)



NASA/JPL/MSSS

Adapted from a Slide by M. Maimone

Driving Modes:

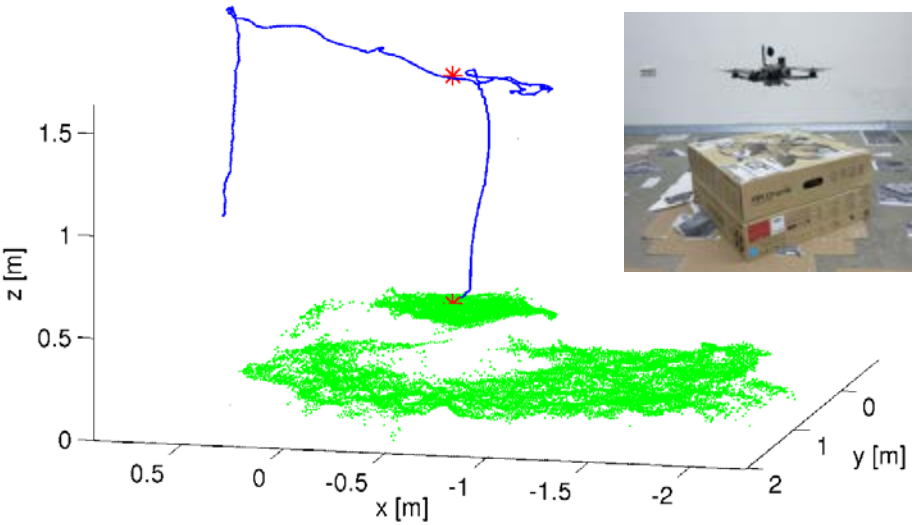
- **Blind Drive** (planned by ground)
- **Autonav** (uses on-board perception and terrain analysis)
- **Visodom** (uses on-board perception to detect slip)

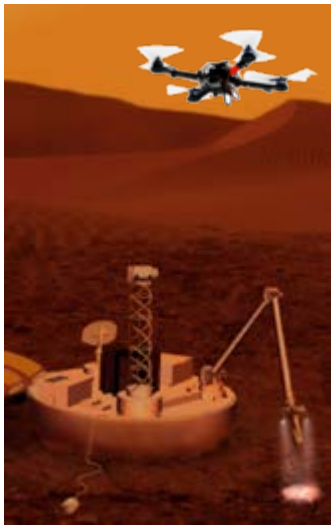
Above-Surface Mobility

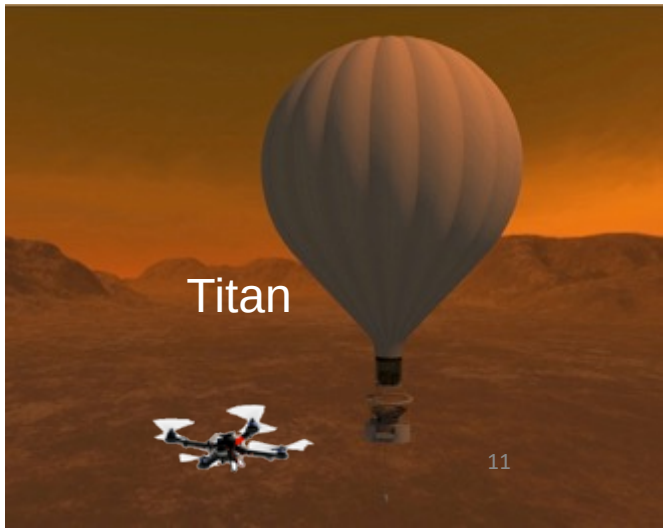
Rotorcraft and Balloon Mobility Research

Research and Development

- **Multiple applications:** (a) terrestrial (defense, intelligence, commercial, and science), and (b) planetary (Mars, Titan, and Venus)
- **Capabilities:** visual-inertial localization combines images with IMU for better estimate; autonomous landing with obstacle avoidance







Other Mobility Research

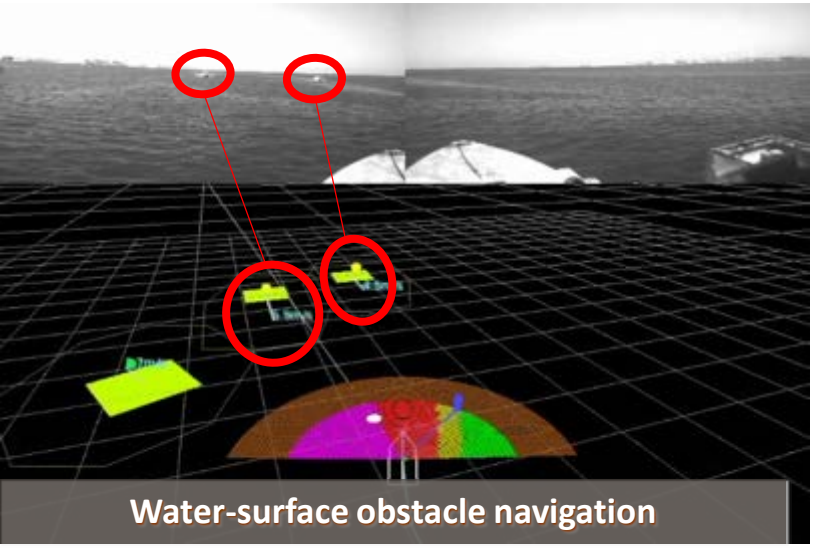
Extreme-terrain, Micro-gravity, Water-surface, and Underwater

Autonomy TIM

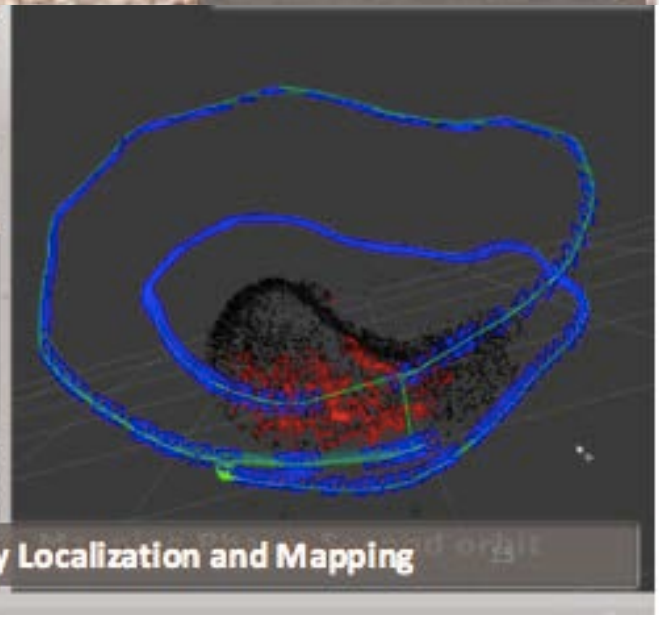
Research and Development

- **Tethered mobility** for accessing extreme terrains (e.g. caves, crevasses, and skylights): autonomous mobility, tether management, docking and sampling
- **Microgravity mobility** localization, mapping, and hazard assessment
- **Water-surface/underwater** navigation and obstacle avoidance using sonar

Extreme-terrain mobility



Water-surface obstacle navigation



Micro-gravity Localization and Mapping

Manipulation

Perception, object handling and assembly

Research and Development

- **Dexterous manipulation:** autonomous object detection, motion planning, and dual-arm contact task execution. Demonstrated examples include tire change-out by finding drill on table, picking it up and using it to unscrew lug nuts; then using dual arms to replace tire
- **Applications** include in-space assembly, repair and maintenance

Manipulation

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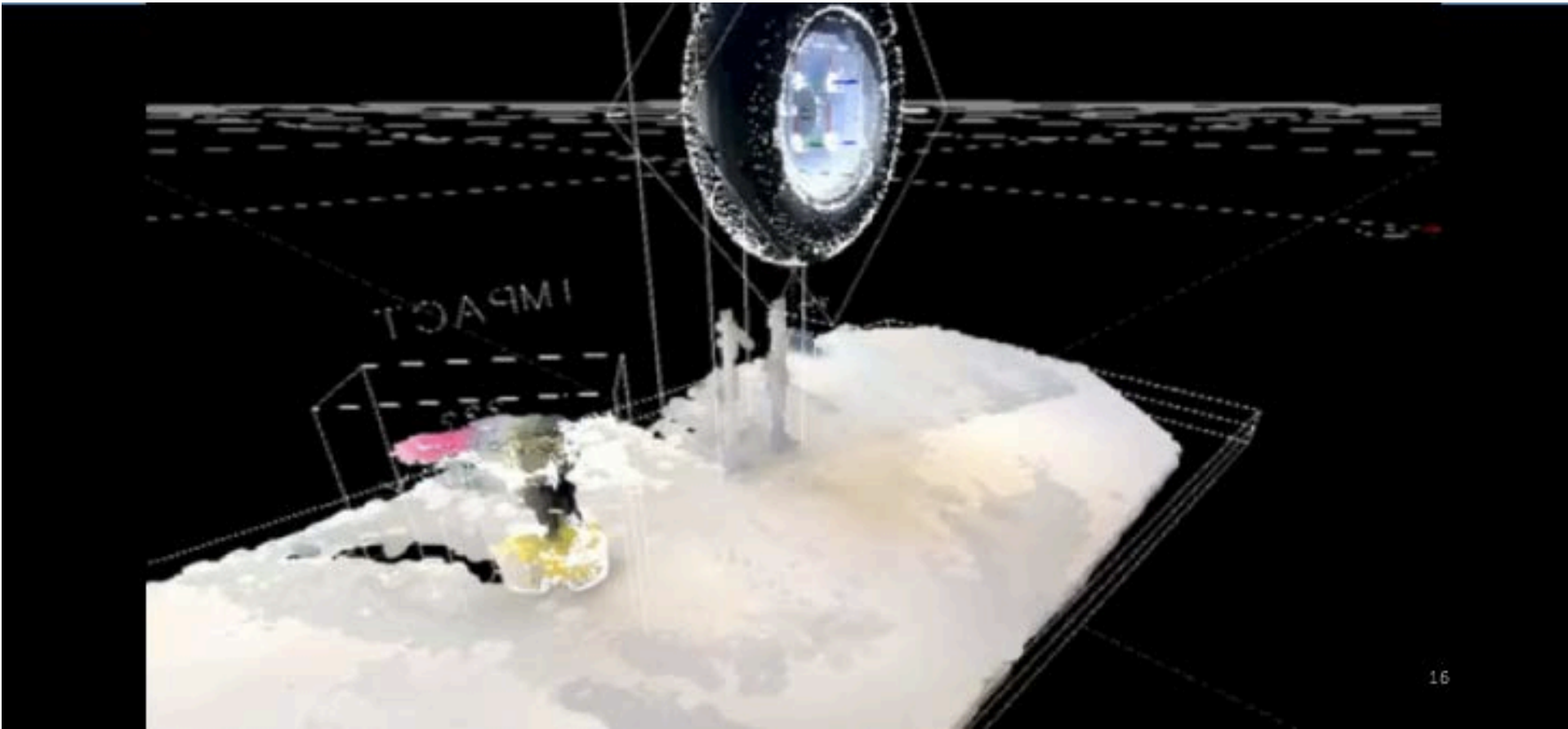
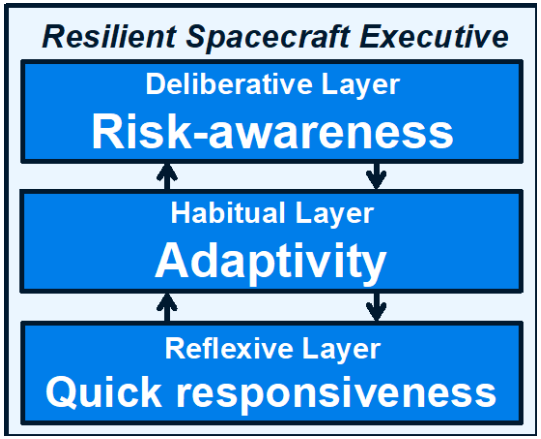


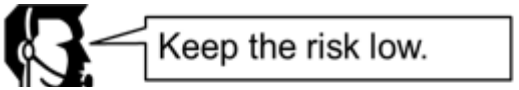
System

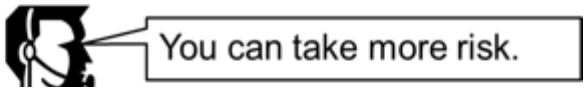
Resilient Spacecraft Executive

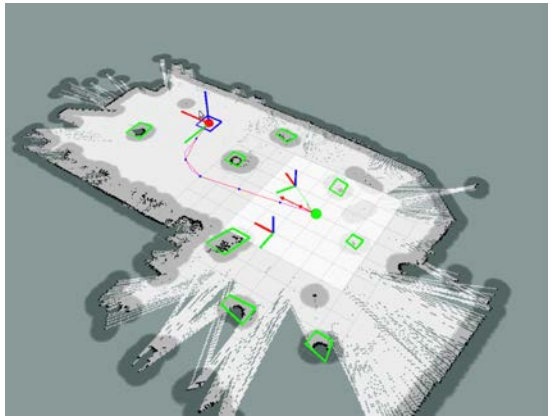
Research and Development

- Adapt to component failures to allow graceful degradation
- Accommodate environments, science observations, and spacecraft capabilities that are not fully known in advance
- Can make risk-aware decisions without ground intervention

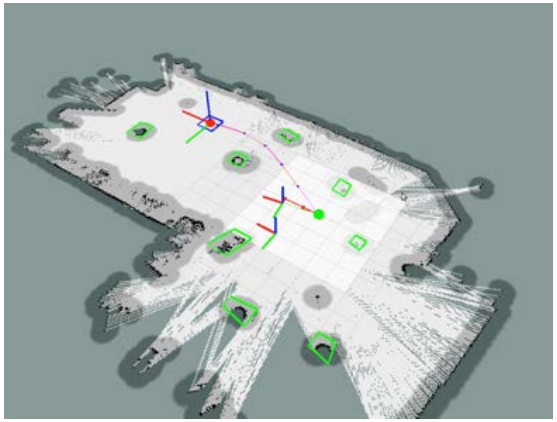








Low Risk



High Risk

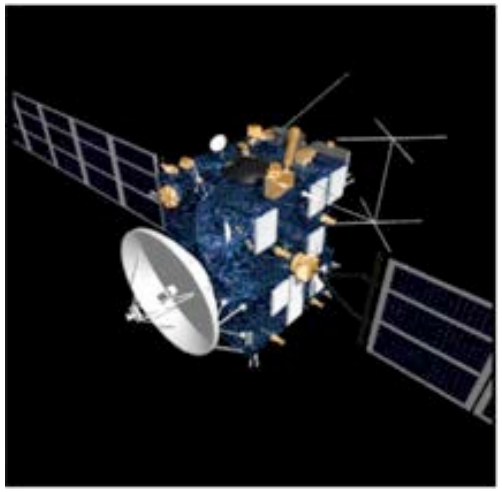
System adapts its behavior depending on acceptable level of risk

System

Activity and Resource Management

Flight

- **DSN:** manages and schedules over 500 activities per week, 300 project service requirements, 38 project users
- **1998 DS1 RAX:** planner/scheduler, smart executive, mode identification and recovery
- **2003– EO-1:** onboard data analysis; recognize science events; automated planning to re-task spacecraft
- **2014 Rosetta Mission:** automated ground-based scheduling for science planning that manages resources

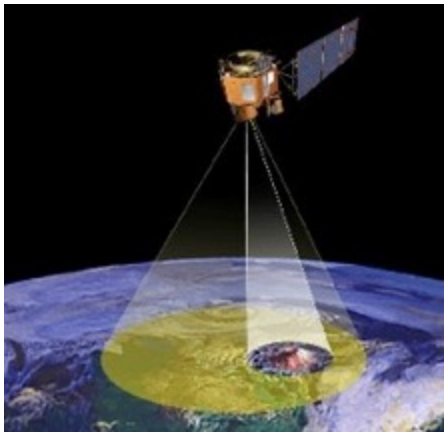


Rosetta spacecraft

Research and Development

- Agile Science using geometric constraints
- Health state awareness via model-based reasoning

DS
N



E0-1 satellite

Deep Space One

Multiple Systems

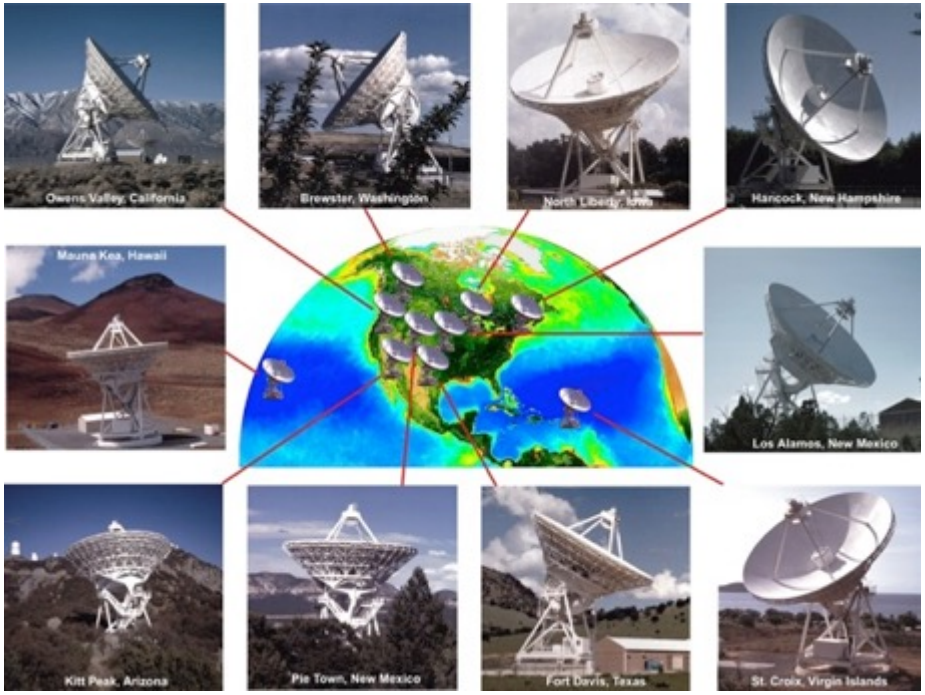
Coordinated Measurements

Terrestrial Deployment

- **2011 Coordinated Radio Telescopes for VLBA:** listens to fast radio transients to detect gamma-ray burst, radio pulsars, or possibly merging black holes
- **2014 Palomar Transient Factory:** real-time signal classifier to distinguish real astronomical transients from false positives

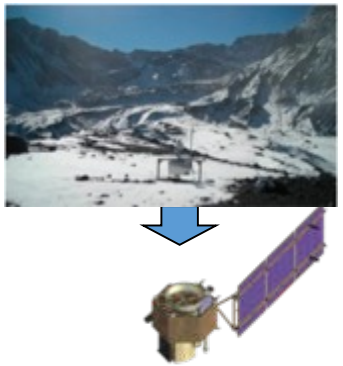
Research and Development

- **Network** space/air/marine/ground **sensors** to an autonomous satellite observation response capability and tie into worldwide disaster monitoring systems for wildfires, floods, volcanoes; repoint spacecraft in response to ground sensors



ASTRON / Curtin University / NRAO / JPL

Image: NRAO

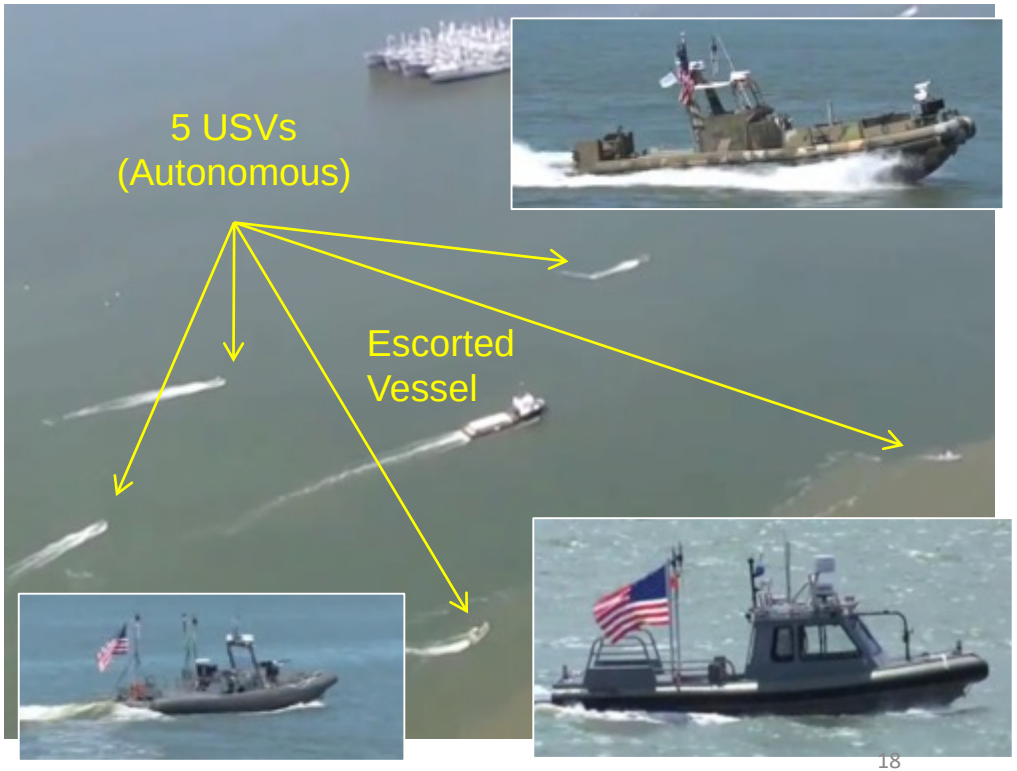


Multiple Systems

Coordinated Activities

Research and Development

- Multi-agent mission planning and task decomposition and allocation to heterogeneous platforms
- Long-range 3D perception with multispectral cameras (600 m)
- Path planning with dynamic obstacle avoidance obeying boating rules of the road
- Maintains formation
- Deliberative activity planning for area survey: subsea surveys with dynamic replanning based on vehicle and environmental conditions



Perception

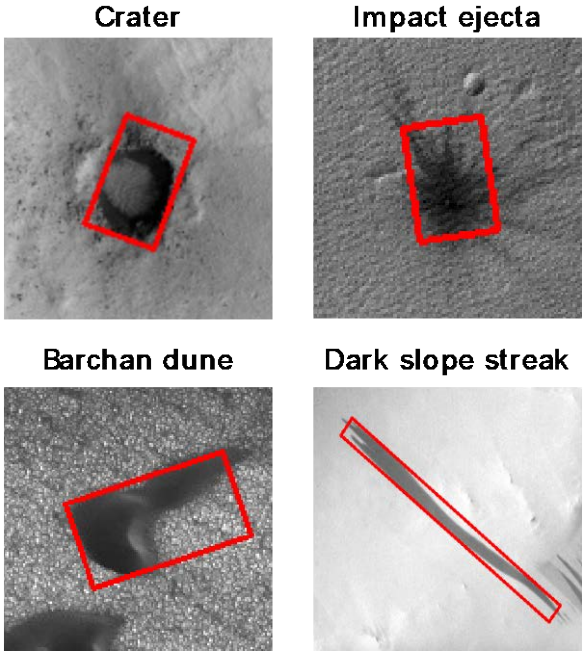
Event Detection and Response

Flights

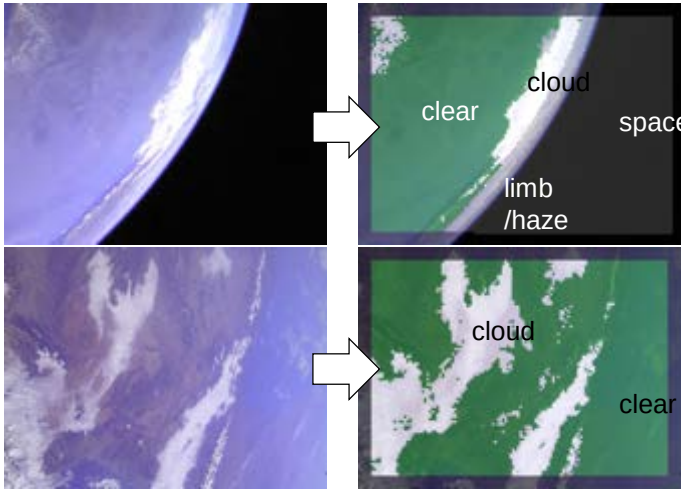
- **2004 Mars Exploration Rovers:** dust devil and cloud detection; automatic targeting
- **2015 Mars Science Laboratory:** intelligent targeting and imaging; identify rock targets through image analysis, take higher res images
- **2015 IPEX:** onboard image analysis to identify surface features and excise clouds

Research and Development

- Machine learning classification of image landmarks
- Real-time data analysis for onboard screening of cloud-contaminated data to improve science yield



IPEX



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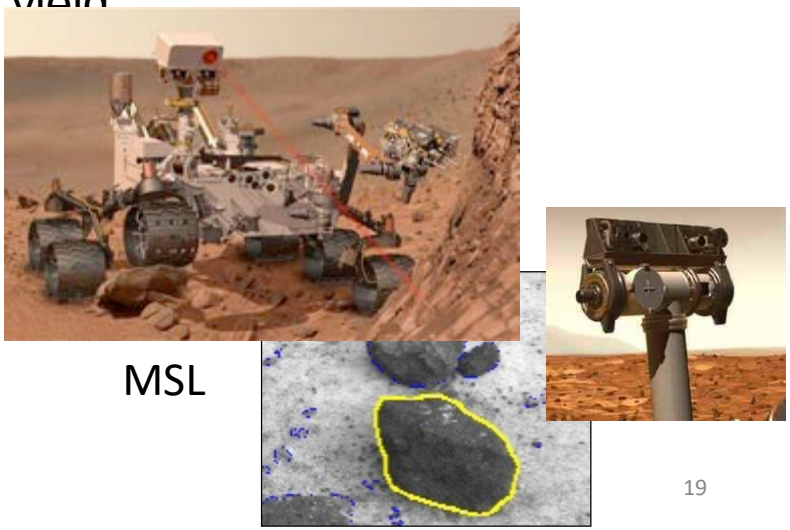
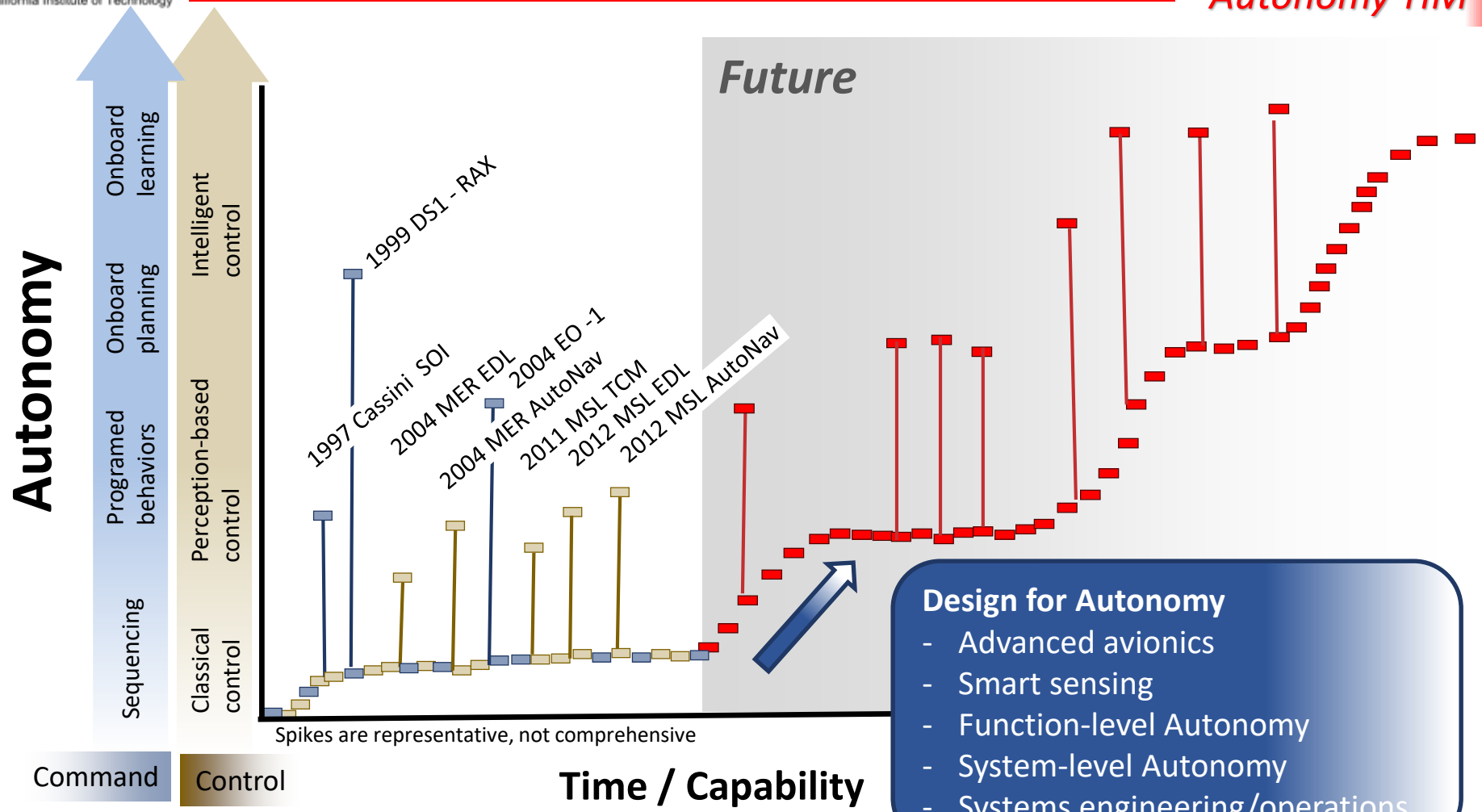


Still a Long Way to Go for Autonomy



Design for Autonomy

- Advanced avionics
- Smart sensing
- Function-level Autonomy
- System-level Autonomy
- Systems engineering/operations

JPL's autonomy development has achieved specific project needs, but has not had a large impact on baseline operations

Summary

- NASA's vision of future human and robotic exploration is exciting, yet challenging
- Each mission type has different needs, but autonomy viewed by all as an enabler
- Elements of autonomy have been developed/infused
  - Perform critical functions when no other option
  - Point designs are inefficient
- Agency lacks end-to-end autonomy capability
  - Depend on on-board decisions to respond *in situ*
  - React to uncertainty
  - Implement appropriate, optimal functions (V&V)
  - Challenging cost caps
- This TIM provides opportunity to share advancements and pursue collaborations.

Europa Lander

Mars Ascent Vehicle

Titan submarine

To have a broader impact, NASA needs a coordinated, cross-discipline strategy to enable autonomy

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California Institute of Technology