

2023 Ground Software Architecture Workshop (GSAW)

# Autonomy & Automation in Deep Space Mission Operations

March 27, 20223

Seung H. Chung, Planning & Execution Systems Section Manager



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### Jet Propulsion Laboratory California Institute of Technology



# Psyche

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Launch: 2023.10.10 Target: 16 Psyche **Type**: Orbiter Arrival: 2029.08 Instruments Multispectral Imager Gamma Ray and Neutron Spectrometer Magnetometer X-band Gravity Science Investigation

**Deep Space Optical** Communication (DSOC)



# **NISAR - NASA-ISRO Synthetic Aperature Radar**

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### Launch: 2024 Target: Earth Type: Orbiter

### Instruments

L-band (24-cm wavelength) Polarimetric Synthetic Aperture Radar

S-band (12-cm wavelength) Polarimetric Synthetic Aperture Radar

# **Europa Clipper**

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## Launch: 2024.10.06

### Target: Europa, Jupiter

### Type: Orbiter

### **JOI:** 2030.04.11

### Instruments

Plasma Instrument for Magnetic Sounding (PIMS)

Europa Clipper Magnetometer

Mapping Imaging Spectrometer for Europa (MISE)

Europa Imaging System (EIS)

Radar for Europa Assessment and Sounding: Ocean to Nearsurface (REASON)

Europa THermal Emission Imaging System (E-THEMIS)

MAss SPectrometer for

Planetary EXploration/Europa (MASPEX)

Europa Ultraviolet Spectrograph SUrface Dust Mass Analyzer (SUDA)



Pre-Decisional Information – For Planning and Discussion Purposes Only

# **Mars Sample Return**

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### Planned **Target**: Mars **Type**: Orbiter, Lander, Helicopter/Rover, Launcher

**Launch**: 2027 – 2028

# **Automation and Autonomous Around Us**

With various degree of automation and autonomy



- Automatic Train Operation
- Airliner Autopilot, Autoland, Auto Takeoff?
- Autonomous Vehicle
- Autonomous Power Plant
- **Autonomous Chemical Plant**
- Automotive Manufacturing Automation and Robots
- Autonomous Warehouse

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# Autonomy & Automation Technologies in the Flight System

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Rajan et al., Remote Agent: An Autonomous Control System for the New Millennium. ECAI 2000, Proceedings of the 14th European Conference on Artificial Intelligence, Berlin, Germany, August 20-25, 2000

# **DS1 Remote Agent Experiment**

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### Technology

- PS Automated Planning and Scheduling
- EXEC Automated plan execution and monitoring
- MIR Model-based diagnosis and reconfiguration

# Mission HeritageDS1



https://ai.jpl.nasa.gov/public/projects/ase/

# **ASE** (Autonomous Science Experiment)

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### Technology

- Onboard Science Feature detection
- CASPER Automated planning and scheduling
- SCL Plan execution and fault protection

# Mission HeritageEO-1

### **Conventional Navigation**

### **Autonomous Navigation**



https://www.jpl.nasa.gov/nmp/ds1/tech/autonav.html

# **Deep Space AutoNav** (Autonomous Navigation)

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### Technology

- Image processing
- Orbit determination
- Maneuver planning and execution

### **Mission Heritage**

- DS1
- Stardust
- Deep Impact / EPOXI
- ASTERIA



https://mars.nasa.gov/mars2020/timeline/landing/entry-descent-landing/

## Mars EDL (Entry Descent and Landing)

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### Technology

- Guided entry
- Parachute descent
- Powered descent
- Sky Crane and Flyaway

### **Mission Heritage**

- MSL
- M2020

## MARS 2020 ROVER TERRAIN RELATIVE NAVIGATION



https://robotics.jpl.nasa.gov/what-we-do/flight-projects/mars-2020-rover/terrain-relative-navigation/

## **TRN** (Terrain Relative Navigation)

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### Technology

- Lander Vision System Localization
- Safe Target Selection

### **Mission Heritage** M2020

https://www-robotics.jpl.nasa.gov/what-we-do/flight-projects/mars-2020-rover/m2020mobility/

## Rover AutoNav (Autonomous Navigation)

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### Technology

- Stereo vision
- Visual odometry
- Hazard assessment
- Path planning

### **Mission Heritage**

- MER
- MSL
- M2020



https://mars.nasa.gov/technology/helicopter/

# **Ingenuity Mars Helicopter**

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jpl.nasa.gov

### Launch: 2020.07.30 Target: Mars Type: Helicopter First Flight: 2021.04.19



Francis, Raymond et al. "AEGIS autonomous targeting for ChemCam on Mars Science Laboratory: Deployment and results of initial science team use." Science Robotics 2 (2017).

## **AEGIS** (Autonomous Exploration for Gathering Increased Science)

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### Technology

- Target Feature detection
- Target prioritization
- Target pointing determination

### **Mission Heritage**

- MER
- MSL
- M2020



https://ai.jpl.nasa.gov/public/projects/m2020-scheduler/



# M2020 On-Board Planner

### Technology

- Automated planning and scheduling
- Automated plan executive

### **Mission Heritage**

M2020 (not yet deployed)

# Flight System Automation & Autonomy – Notional



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# **Functional vs. System-Level Automation & Autonomy**





Functional (Subsystem) Autonomy & Automation System-level Autonomy & Automation

# Functional vs. System-Level Automation & Autonomy



- Deep Space AutoNav
- Mars EDL (Entry Descent and Landing)
- **TRN** (Terrain Relative Navigation) •
- **Rover AutoNav**

.

- Ingenuity Mars Helicopter •
- AEGIS (Autonomous Exploration for Gathering Increased Science)

- DS1 RAX (Remote Agent Experiment)
- ASE (Autonomous Science Experiment) .
- M2020 On-Board Planner



Functional (Subsystem) Autonomy & Automation System-level Autonomy & Automation

# Autonomy & Automation Technologies in the Ground System

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https://ai.jpl.nasa.gov/public/projects/aspen/

# **ASPEN** (Automated Scheduling and Planning ENvironment)

### Technology

 Automated activity planning and scheduling

### **Mission Heritage**

- EO-1
- Rosetta



https://ai.jpl.nasa.gov/public/projects/clasp/

# **CLASP** (Compressed Large-scale Activity Scheduling and Planning)

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### Technology

 Automated observation planning and scheduling

### **Mission Heritage**

- NISAR
- ECOSTRESS
- EMIT
- OCO-3

### TimeLines

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https://ai.jpl.nasa.gov/public/projects/m2020-scheduler/

# M2020 Copilot

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### Technology

- Stochastic plan analysis
- Activity prioritization for robust planning

### **Mission Heritage**

M2020 (not yet deployed)

# Automating Deep Space Mission Operations

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# **Reasons for Automation & Autonomy**

Many argue that automation and autonomy...

- Enables missions otherwise not possible
- Reduces operations cost

# **Operations Cost of Deep Space Missions**

Operations cost growth concerns

- B. Barley et al., Life Cycle Cost Growth Study for the Discovery and New Frontiers Program Office, February 2010.
- R. Bitten et al., Phase E Cost Analysis for NASA Science Missions, AIAA Space 2012 Conference & Exposition, Pasadena, CA, September 2012.
- J. F. McNeill et al., Understanding Cost Growth During Operations of Planetary Missions: An Explanation of Changes. IEEE Aerospace Conference, Big Sky, Montana. March 2013.
- New Frontier 5 Phase E operations cost capped at \$300M in **FY22\$**

# Flight and Ground Automation & Autonomy





Flight System Ground System

# **Range of Automated Ground System**



# **Cost of Greater Ground Automation & Autonomy**





## Cost of developing and maintaining the system under control

# Cost of developing and maintaining the control

# **Tradeoff between Flight/Ground Automation & Autonomy**



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Flight System Ground System

# **Tradeoff between Flight/Ground Automation & Autonomy**





Latency Observability Controllability Reliability Maintainability **Computing Capability** 

# **Challenges with Automated Operations**

Sample of common concerns...

- Safety of the flight system
- Depletion of resources
- Allocation and management of HW lifetime
- Handling anomalies
- Operating degraded or faulty flight system
- Knowledge of flight system state and behavior when manual override is required
- Quality of mission outcomes

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# **Challenges with Automated Operations**

## Anomaly Handling / Trust / Return on Investment

Anomaly Detection and Recovery

- Operator complacency and skill atrophy
- Operator's inability to understand and manipulate autonomous system behavior and state Trust
- Mission success... autonomous action/inaction that may lead to mission failure
- Quality of science return given the nature of scientific "exploration" of deep space... the unknown

Return on Investment... Is it worth the trouble?

Reusability of automation and autonomy across missions, given heterogeneous robotic spacecraft and instruments

# **Challenges with Automated Operations** How about **explainability**?

- Explain about an automated system...
  - How it works
  - When it works or doesn't work
  - Why it works or doesn't work
- Examples to consider...
  - Users' understanding of PID controllers and Kalman filters
  - Drivers' understand adaptive cruise control system

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# **Success Criteria for Automated Operations** Addressing Anomaly Detection & Recovery and Return on Investment

- Standard automation and autonomy behavior
- Standard interface to flight system across missions... standardizing the telemetry and command for common flight system behavior
- Multi-mission operators and operations infrastructure
- Infrastructure to train operators and aid in retaining the skill and knowledge

# **Success Criteria for Automated Operations** Addressing **Trust**

- "Bounded" autonomy behavior for safety and risk assessment
  - Uncertainty assumption and characterization •
  - Convergence or stability criteria
  - Soundness guarantees of the behavior
- Fault protection for automation and autonomy behavior... i.e. monitoring deviation from the designed boundary of autonomy behavior
- Operations experience with gradual increase in automated operations
- Scientists in the loop operations

# **Automation and Autonomy Techniques**

Generalized high-level classification of the techniques

- Procedural
- Data-driven
  - System identification
  - Feature recognition / Classification
- Model-based
  - **Estimators**
  - Controllers
  - Activity planning and scheduling<sup>†</sup>
  - Path/Motion planning<sup>†</sup>

† Traditionally model-based techniques have been used, but more data-driven and hybrid approaches are being adopted

# Challenges for Automation and Autonomy Techniques How do we bound the automated behavior given the challenges?

- Procedural
  - Robustness
- Data-driven
  - Data availability
  - Data coverage
- Model-based
  - Model structure and complexity
  - Model creation<sup>†</sup>
  - Model verification<sup>+</sup>

† Data-driven approach commonly used

# What should be next?

Continue developing automation & autonomy!



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Assess overall benefits, risks, and cost

Bound the behavior Grow from functional to system-level

Continue developing automation & autonomy to enable missions and reduce operations cost!



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