Autonomy & Automation in Deep Space Mission Operations

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Seung H. Chung,
Planning & Execution Systems Section Manager
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)
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

NISAR - NASA-ISRO Synthetic Aperature Radar
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 Near-surface (REASON)
Europa THERmal Emission Imaging System (E-THEMIS)
MAss SPectrometer for Planetary EXploration/Europa (MASPEX)
Europa Ultraviolet Spectrograph
SURface Dust Mass Analyzer (SUDA)
Mars Sample Return

Launch: 2027 – 2028
Planned
Target: Mars
Type: Orbiter, Lander, Helicopter/Rover, Launcher

Pre-Decisional Information – For Planning and Discussion Purposes Only

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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
- …
Autonomy & Automation Technologies in the Flight System
DS1 Remote Agent Experiment


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

Mission Heritage
• DS1
ASE (Autonomous Science Experiment)


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

Mission Heritage
- EO-1
Deep Space AutoNav (Autonomous Navigation)

Technology
• Image processing
• Orbit determination
• Maneuver planning and execution

Mission Heritage
• DS1
• Stardust
• Deep Impact / EPOXI
• ASTERIA

Mars EDL (Entry Descent and Landing)

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

Mission Heritage
- MSL
- M2020

https://mars.nasa.gov/mars2020/timeline/landing/entry-descent-landing/
Technology
• Lander Vision System Localization
• Safe Target Selection

Mission Heritage
M2020

TRN (Terrain Relative Navigation)

Rover AutoNav (Autonomous Navigation)


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

Mission Heritage
- MER
- MSL
- M2020
Ingenuity Mars Helicopter

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

https://mars.nasa.gov/technology/helicopter/
**AEGIS** (Autonomous Exploration for Gathering Increased Science)


**Technology**
- Target Feature detection
- Target prioritization
- Target pointing determination

**Mission Heritage**
- MER
- MSL
- M2020
M2020 On-Board Planner

Technology
- Automated planning and scheduling
- Automated plan executive

Mission Heritage
- M2020 (not yet deployed)

A schedule of when activities can run

Predicted energy, Predicted data volume

Flight System Automation & Autonomy – Notional

Flight System

Flight Software

Science Target & Data Management  Navigation  ...  Subsystem Autonomy

Integrated Health & State Management  Integrated Planning & Execution

Ground Data System

Mission System

Telemetry / Data
State / Health

Commands
Goals

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Functional vs. System-Level Automation & Autonomy
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
Autonomy & Automation Technologies in the Ground System
ASPEN (Automated Scheduling and Planning ENvironment)

Technology
• Automated activity planning and scheduling

Mission Heritage
• EO-1
• Rosetta

CLASP  (Compressed Large-scale Activity Scheduling and Planning)

Technology
• Automated observation planning and scheduling

Mission Heritage
• NISAR
• ECOSTRESS
• EMIT
• OCO-3
Technologies:
- Stochastic plan analysis
- Activity prioritization for robust planning

Mission Heritage:
- M2020 (not yet deployed)

### M2020 Copilot

Automating Deep Space Mission Operations
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

- **New Frontier 5 Phase E operations cost capped at $300M in FY22**
Flight and Ground Automation & Autonomy

Flight System
- Flight Software
  - Science Target & Data Management
  - Navigation
  - ... Subsystem Autonomy
  - Integrated Health & State Management
  - Integrated Planning & Execution

Ground Data System
- Integrated Health & State Management
- Integrated Planning & Execution
- ... Subsystem Autonomy
- Science Target & Data Management
- Navigation

Mission System
- Telemetry / Data
- State / Health

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Range of Automated Ground System

- System Under Control
- Control System
- Fully Autonomous

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Cost of Greater Ground Automation & Autonomy

Cost of developing and maintaining the system under control vs. Cost of developing and maintaining the control system

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

- Latency
- Observability
- Controllability
- Reliability
- Maintainability
- Computing Capability
- Cost
- ...

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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
- …
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
  - …
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

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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†
  • Path/Motion planning†

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

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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†
  - Model verification†

† Data-driven approach commonly used
What should be next?

Continue developing automation & autonomy!

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

But be sure to…
- Bound the behavior
- Grow from functional to system-level
- Assess overall benefits, risks, and cost