Autonomous Mission Operations Roadmap

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Executive Summary

• *Autonomous Mission Operations* is the capability of flight controllers and crews to manage a crewed mission with minimal reliance on Earth-based Mission Control.
  – Autonomy is accomplished by automating vehicle functions, and by transitioning responsibilities from Mission Control to crew.

• This capability is *enabling* for missions to NEAs and Mars.

• Near-term capability demonstrations onboard ISS and using ground-based analogs are funded. Gaps have been identified; filling them requires further funding.
Defining Autonomous Mission Operations
Mission Operations Capabilities

- **Monitoring Displays:** displays are groups of commands and telemetry / data used by flight controllers and crew to monitor and command a subset of spacecraft systems in conjunction with a specific activity.

- **Manage Faults:** Failures are the unacceptable performance of an intended function. Failures are caused by faults.
  - Fault management includes detection, isolation and recovery from faults.
  - Managing faults is often done using pre-defined fault management procedures.
Mission Operations Capabilities

- **The Plan** (or Timeline) is the list of all activities occurring during the mission including those performed by the crew, occurring on the spacecraft (e.g. maneuvers, docking/undocking), or impact the mission (e.g. communications coverage changes).
  - Activities last from 5 minutes to tens of minutes.
  - Activities refer to procedures or procedure steps.

- **Perform Procedures**: procedures are step-by-step instructions to perform a specific task.
  - Crew and flight controllers perform procedures during the mission.
  - Procedure steps take seconds to minutes.
Mission Operations
Performance Parameters

Telemetry is shown on Displays.
Failures are shown on Displays.
Commands are issued from Displays.
Commands are organized into Procedures.
Failures trigger Procedures.
Procedures are organized into Plans.
Operational Guidelines constrain Plans.
Operational Guidelines constrain Procedures.
Failures disrupt Plans.
Capability Discriminators

- Low time delay
  - <10 seconds 1-way light-time
  - Based on 2012 AMO experiment; flight controllers dispensed with 10 second test case because it was deemed identical to ISS operations
  - Covers LEO and Lunar DRMs
- NEA without EVA
  - < 8 minutes 1-way light-time
  - DRMs assume NEA operations correspond to 1 Astronomical Unit (AU) distance from Earth, which incurs 8 minute 1-way delay
- NEA with EVA
  - EVA increases complexity of missions compared to non-EVA
- Mars without EVA
  - <22 minutes 1-way light-time
- Mars with EVA
Gap Fillers

Analysis
## International Space Station

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Command (distinct types)</td>
<td>70,000</td>
</tr>
<tr>
<td>Telemetry (distinct types)</td>
<td>177,000</td>
</tr>
<tr>
<td>Procedures (distinct)</td>
<td>4,000</td>
</tr>
<tr>
<td>Operational Guidelines / Constraints</td>
<td>1,000 (Flight rules and crew planning constraints)</td>
</tr>
<tr>
<td>Failure messages (distinct types)</td>
<td>18,000 (estimated from emergency books)</td>
</tr>
<tr>
<td>Displays (ground)</td>
<td>1,500</td>
</tr>
<tr>
<td>Displays (onboard)</td>
<td>3,000</td>
</tr>
<tr>
<td>Plan size (activities / day)</td>
<td>200 (estimated from crew, power and attitude plans)</td>
</tr>
</tbody>
</table>

These parameter values are for USOS only.
Approach to Capability Growth Assessment

- Capability thresholds for each class of DRMs were derived by scaling ISS capability.
- Scaling was derived from:
  - Crew size reduction (4 for Exploration, 6 for ISS)
  - Increased autonomy for NEA and Mars DRMs
  - Reduced capability required if EVA not part of DRMs
Scaling relative to ISS for Autonomous Ground Operations

<table>
<thead>
<tr>
<th>Time Delay/ Capability</th>
<th>Low &lt;10 sec</th>
<th>NEA w/o EVA &lt; 8 min</th>
<th>NEA w EVA &lt; 8 min</th>
<th>Mars w/o EVA &lt; 22 min</th>
<th>Mars w EVA &lt; 22 min</th>
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</thead>
<tbody>
<tr>
<td>Desired</td>
<td>ISS</td>
<td>ISS</td>
<td>ISS</td>
<td>ISS</td>
<td>ISS</td>
</tr>
<tr>
<td>Threshold</td>
<td>2/3 ISS</td>
<td>1/2 ISS</td>
<td>2/3 ISS</td>
<td>2/3 ISS</td>
<td>ISS</td>
</tr>
<tr>
<td>State of the Art</td>
<td>ISS</td>
<td>1/2 ISS</td>
<td>1/2 ISS</td>
<td>1/2 ISS</td>
<td>1/2 ISS</td>
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Scaling relative to ISS for Autonomous Crew Operations

- NEA and Mars DRM assume increased autonomy.
  - Crew cognizance of Operations Constraints and Guidelines *increases* due to time delay.
  - More vehicle automation *reduces* required crew cognizance of Commands and Telemetry.
  - This manifests as reductions in effort to Monitor Displays and Perform Procedures.
Scaling relative to ISS for Autonomous Crew Operations

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<tbody>
<tr>
<td></td>
<td>&lt;10 sec</td>
<td>&lt; 8 min</td>
<td>&lt; 8 min</td>
<td>&lt; 22 min</td>
<td>&lt; 22 min</td>
</tr>
<tr>
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</tr>
<tr>
<td>State of the Art</td>
<td>ISS</td>
<td>1/2 ISS</td>
<td>1/2 ISS</td>
<td>1/2 ISS</td>
<td>½ ISS</td>
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<td>1/2 ISS</td>
<td>1/2 ISS</td>
<td>1/2 ISS</td>
<td>½ ISS</td>
</tr>
<tr>
<td>% ops guidelines</td>
<td>0</td>
<td>20%</td>
<td>20%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>% commands, telemetry</td>
<td>100%</td>
<td>80%</td>
<td>80%</td>
<td>50%</td>
<td>50%</td>
</tr>
</tbody>
</table>
Scaling relative to ISS for Autonomous Crew Operations

![Graph showing crew capability scaling relative to ISS for various time delays and locations.](image)
Gap Fillers

Activity
Activities on Capability Roadmap

• Extending autonomy capability requires:
  – Transitioning responsibility from ground to crew (e.g. autonomous procedure execution)
  – Automating functions done by people (e.g. procedure automation)
  – Expanding autonomy from simple to complex tasks (e.g. from single procedures to managing entire system)
  – Scaling autonomy from smaller to larger systems (e.g. one power bus to four)
  – Expanding autonomy to more types of systems (e.g. power, ECLSS and Thermal)
Capability Progression / Dependency
– Autonomous Mission Operations

Initial Exploration Missions
Extending Reach Beyond LEO
Into The Solar System

Legend:
Gold Text - Current
Orange Text – Near-Term
Blue Text – Long-Term
Activity (Current: ISS)

• Comm Delay Characterization
  – Observe impact of time delay on team interaction

• Autonomous Procedures
  – Revise existing procedures for ISS crew execution without ground assistance

• ISS Texting
  – Develop texting protocols; demonstrate texting to and from ISS

• Crew Self Scheduling
  – Compare multiple crew self-scheduling technologies
Activity  
(Near-Term: ISS)

• AMO TOCA-SSC
  – Demonstrate crew autonomous management of TOCA and monitoring of SSCs

• AMO-EXPRESS
  – Demonstrate ground initiated powerup and configuration of EXPRESS rack
  – Set stage for crew initiated experiment using novel operations technology
Activity
(Long-Term: ISS)

• Autonomous Systems and Operations (ASO)
  • Demonstrate crew autonomous management of complex ISS system (TBD)

• Autonomous Logistics Management (ALM)
  • Demonstrate crew use of static and mobile RFID readers onboard ISS to track logistics

• Autonomous Remote System Management (ARSM)
  • Demonstrate crew ability to teleoperate systems without ground assistance
Activity
(Long-Term: ISS)

• Autonomous Extra Vehicular Activity (EVA)
  – Demonstrate tools to assist ISS crew in autonomously conducting EVA (in order to demonstrate capability to do so at high time delay)

• Autonomous Flight Dynamics (AFD)
  – Demonstrate tools to assist crew in performing vehicle maneuvers at high time delay
Activity
(Current: Ground)

- EFT-1 Advanced Caution and Warning (ACAWS)
  - Demonstrate advanced caution and warning tools during EFT-1
- EM-1 ACAWS
  - Demonstrate advanced caution and warning tools during EM-1
Activity
(Long Term: Ground)

- **VSM (Power)**
  - Demonstrate autonomous power systems management of an Earth-Moon L2 vehicle

- **VSM (Life Support)**
  - Demonstrate autonomous life support management of an Earth-Moon L2 vehicle
# Gap Filler Activities and Capabilities

## Autonomous Crew Operations

<table>
<thead>
<tr>
<th>Parameters Activities</th>
<th>Telemetry</th>
<th>Commands</th>
<th>Displays</th>
<th>Procedures</th>
<th>Plan Steps</th>
<th>Operational Constraints</th>
<th>Faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMO TOCA-SSC (Monitor Displays, Perform Procedures, Manage Faults)</td>
<td>&lt;100</td>
<td></td>
<td>&lt;10</td>
<td>&lt;100</td>
<td></td>
<td>&lt;100</td>
<td>&lt;100</td>
</tr>
<tr>
<td>AMO EXPRESS (Perform Procedures, Manage Faults)</td>
<td>&lt;100</td>
<td>&lt;100</td>
<td></td>
<td>&lt;10</td>
<td></td>
<td>&lt;10</td>
<td></td>
</tr>
<tr>
<td>Auto Procedures (Perform Procedures, Manage Faults)</td>
<td>&lt;1000</td>
<td>&lt;100</td>
<td></td>
<td>&lt;10</td>
<td></td>
<td>&lt;1000</td>
<td></td>
</tr>
<tr>
<td>Crew Self Scheduling (Execute Timeline)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>TBD</td>
<td>TBD</td>
</tr>
</tbody>
</table>

## Autonomous Ground Operations

<table>
<thead>
<tr>
<th>Parameters Activities</th>
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<th>Plan Steps</th>
<th>Operational Constraints</th>
<th>Faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFT-1 ACAWS (Manage Faults)</td>
<td>&lt;1000</td>
<td>&lt;10</td>
<td>&lt;10</td>
<td></td>
<td></td>
<td></td>
<td>&lt;10000</td>
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</tbody>
</table>
Gap Fillers

Costs
Main Costs to Fill the Gaps

• Autonomous Crew Operations
  – Technology development duration
  – Technology development costs
  – Testing onboard ISS

• Autonomous Ground Operations
  – Testing with ISS
Main Costs to Fill the Gaps

• The pacing items for demonstrating autonomy technology in the presence of time delays of less than 8 minutes are:
  – ISS on-orbit time
  – Availability of a sophisticated human spaceflight simulation on the ground
  – Availability of trained flight controllers and crew to perform experiments.
Inter-SMT Relationships

• Direct relationships
  – EVA demonstrations
  – Human Systems demonstrations
  – Robotic Systems

• Indirect relationships
  – Activities that eliminate tasks (e.g. reduced maintenance of ECLSS hardware)
  – Activities that eliminate operational constraints (e.g. cameras that can operate in low light)
  – Activities that produce automated systems (e.g. automate power distribution)
STMD and I-SMT

• STMD Discussions have commenced
  – TA04,7,11
• Several ISS / International Exploration Working Group (Team 6) concepts have international participation
  – Crew Self Scheduling
  – Autonomous Procedures
  – Advanced Autonomy Software
• One International-SMT proposal suggestion
  – Autonomous Inspection (CSA proposal, joint with Robotics)
In-Space Inspection

A few thoughts
Autonomous In-Space Inspection

• Manage Timeline
  – Can activity be performed when planned?
  – Can Crew decide when to start activity without assistance from ground?

• Perform Procedures
  – Can Crew perform procedures without assistance?
Autonomous In-Space Inspection

• Monitor Displays
  – Can combination of In-Space Inspection system and Crew perform preliminary analysis of images without assistance from ground?
  – Can downlink management be automated without Crew intervention?

• Manage Faults
  – What faults can system help Crew address without assistance from ground?
  – Can faults in In-Space Inspection system be addressed by Crew without ground?
Future Plans

• Former ISS Expert Working Group (Team 6) and AMO SMT will join forces
  – Engagement with international partners will be extended to ESA, Russia
• Interaction with STMD Roadmaps will continue
• Commence engagement with HAT and Evolvable Mars
• Publish this roadmap!
Team

• J. Frank (ARC TI) (Lead)
• M. Lowry (ARC TI)
• D. Alfano (ARC TI)
• M. Schwabacher (ARC TI)
• B. Beuter (ARC TH)
• R. McCann (ARC TH)

• W. Spetch (JSC OM)
• A. Haddock (MSFC EO)
• M Macalyea (MSFC EO)
• D. Korth (JSC DA)
• S. Love (JSC CB)
• L. Morin (JSC CB)
• A. Stroupe (JPL 317)
BACKUP
Definitions of Parameters

- **Commands** – directive to spacecraft or spacecraft subsystem
- **Telemetry** – single data item produced by spacecraft
  - Strictly speaking telemetry is what gets sent to ground
- **Display** – group of commands and telemetry used by flight controller in single tool or part of tool to run mission
- **Procedures** – step by step instructions to perform task
- **Plan** (Timeline) – distinct types of planning are required to create an operations plan (e.g. power, attitude, crew plan, etc.)
- **Operational Constraints and Guidelines** – Generally includes any constraint, e.g. Crew Scheduling Constraints and Ground Rules and Constraints. Plans and procedures must respect / satisfy these constraints.
- **Failures** – loss of function of (part of) a system element
Capabilities and Parameters

<table>
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<tr>
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<th>Operational Constraints</th>
<th>Faults</th>
</tr>
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<tbody>
<tr>
<td>Monitor Displays</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
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<tr>
<td>Perform Procedures</td>
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<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
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<tr>
<td>Execute Timeline</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manage Faults</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

These capabilities must be advanced both onboard (Autonomous Crew Operations) and ground (Autonomous Ground Operations). Transitioning authority, re-scoping ground control roles, increasing onboard automation and increasing ground automation are all needed to grow autonomous operations capability.
(Simple) Relationships between Parameters

- Telemetry
- Commands
- Operational Guidelines/Constraints
- Procedures
- Plans
- Displays
- Triggers
- Failures

Relationships:
- Telemetry is Part-of Commands
- Commands is Part-of Operational Guidelines/Constraints
- Procedures is Part-of Operational Guidelines/Constraints
- Plans is Part-of Operational Guidelines/Constraints
- Displays is Part-of Procedures
- Triggers is Part-of Displays
- Failures is Disrupts Plans

Disrupts:
- Plans is Disrupts Failures
What params and capabilities are missing?

• Knowledge
  – Console handbooks, systems briefs, crib sheets, on-board training, and other forms of knowledge
  – Access to this information will be key to future human spaceflight missions

• Analysis (Models and Simulations)
  – Flight dynamics (attitude and trajectory), consumables estimation, power and thermal models, communications interference
  – Migration of this functionality onboard will be likely to enable future human exploration missions
What params and capabilities are missing?

- Better explanation of how automation reduces required capability
  - Crew: better model for how reduction in telemetry and commands reduces effort to monitor displays, run procedures
  - Crew: automation should reduce effort in managing faults, means we need reduction in faults too
  - Ground: automation / autonomy should reduce effort for ground functions too
Definitions of Parameters

- **Commands** – directive to spacecraft or spacecraft subsystem
- **Telemetry** – single data item produced by spacecraft
  - Strictly speaking telemetry is what gets sent to ground; may need better terminology to distinguish data produced by spacecraft vs telemetry received by ground
  - Computations transform telemetry into other quantities for use in MCC. So there are really 3 ‘classes’ of data item: onboard, telemetry, comps.
- **Display** – group of commands and telemetry used by flight controller in single tool or part of tool to run mission
- **Procedures** – step by step instructions to perform task
  - JSC parlance: ‘Procedures’ are written to be executed by crew
  - JSC parlance: ‘Task-based displays’ used by flight controllers to run procedures.
  - Procedures could be automated or run by hand
- **Timeline (Plan)** – distinct types of planning are required to create an operations plan (e.g. power, attitude, crew plan, etc.)
- **Operational Constraints and Guidelines:** – Generally includes any constraint, e.g. Crew Scheduling Constraints and Ground Rules and Constraints. Plans and procedures must respect / satisfy these constraints.
  - Flight Rules - real time operations guidelines and situation response guidance
  - Groundrules and Constraints - Constraints and boundaries used in plan development and replanning
  - For launch vehicles there are also Launch Commit Criteria (LCCs).
- **Failures** – loss of function of (part of) a system element
(Simple) Relationships Between Parameters

- Telemetry is grouped into displays.
- Commands and telemetry are referenced in Procedures.
- Procedure steps are grouped into single Timeline (Plan) steps.
- Timelines and Procedures must satisfy Operational Guidelines and Constraints.
- Failures disrupt Timelines and Procedures.
- Failures are managed using displays and procedures.