National Aeronautics and Space Administration

FY23 Strategic Initiatives Research and Technology Development (SRTD)

Operations for Autonomy: Spacecraft State Estimation to Support Execution and Understanding of Onboard Decisions

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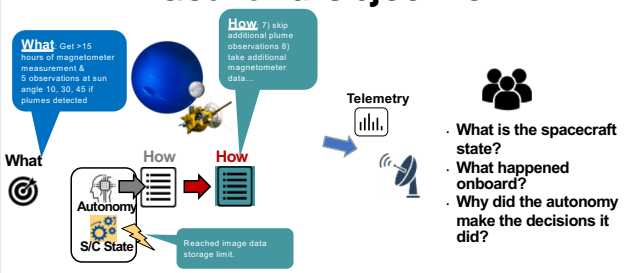
Strategic Focus Area: Operations for Autonomous Spacecraft | **Strategic Initiative Leader:** Rebecca Castano

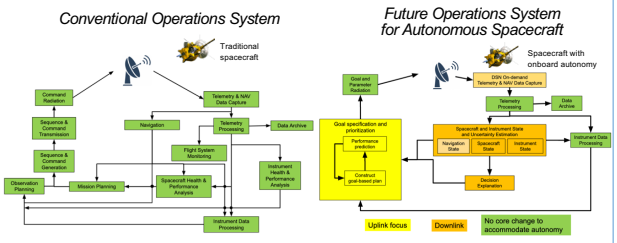
Goal and Objective



Objective: Develop technology to enable operations to

- understand *what* onboard decisions were made and *why*, enabling reconstruction of what the spacecraft executed
- predict the *state* of the spacecraft to inform specification of future science and engineering *goals*.

Background



On-board autonomy *enables* missions such as outer planets **flybys** and **surface operations** in adverse environments when ground-in-the-loop operations are not feasible due to to *bandwidth, latency,* limited *lifetime*

New **tools** and **workflows** needed to: (i) *explain* autonomy decisions, (ii) infer future spacecraft *state* with autonomy in the loop, and (iii) identify *anomalies* that may be hidden by autonomy

Approach

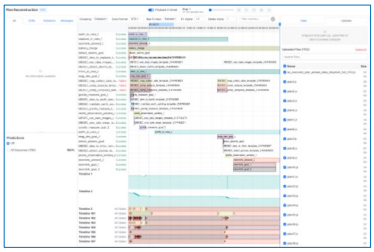
Plan Reconstruction

Goal: "*at-a-glance*" reconstruction of

- What was *planned*
- What was *executed*
- How the spacecraft *state* evolved

Features:

1. Show on-board *plans*
   - Uses existing EVRs for task start, end, status
   - No changes to FSW required
2. Show *predicted* evolution of spacecraft *resources*
3. *Playback* to observe how plans evolved
4. Show which tasks were *executed*, and when
5. Show how spacecraft *resources actually* evolved
   - Kalman filter-based state estimation
   - Plant model uses existing MEXEC models, minimizing additional modeling required
6. Compare with *uplink predictions* for tasks, resources
7. Display relevant *EVRs*

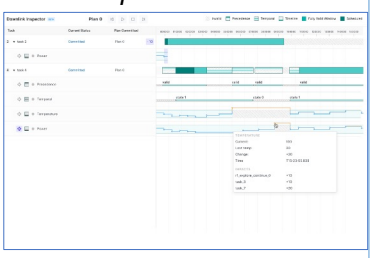


Downlink Inspector

Goal: detailed view of *why* a task was *scheduled* at a given time

Features:

1. Display task *priority*
2. Display *order* in which tasks were scheduled
3. Display *availability windows* for
   a. temporal
   b. precedence
   c. resource constraints
4. Highlight which tasks *affect* a resource (changing the availability)



Selected Findings

1. Once the as-executed sequence is reconstructed, many downlink analysis activities (subsystems health, science analysis) are *not directly affected* by on-board autonomy
2. Downlink operations need *deep understanding* of *on-board autonomy* and *uplinked intent*
3. Many downlink operations that rely on checking for "*nominal*" behavior must *change* to accommodate autonomy
   - "Nominal" becomes "*in family*"
   - Operators instinctively rely on comparing predicts vs. actuals - but what actuals are *relevant*?
4. "Why" has *different meaning* for different roles
   - Providing context can help form *mental models* key to answering "why"
5. Supporting autonomy requires *new GDS tools*
6. *Tight loop* between FSW and GDS development is needed to identify *new telemetry* to support downlink analysis
7. *Modeling* is hard
   - If a tool requires development of new models, adoption becomes challenging

Selected Recommendations

1. Include an "*autonomy engineer*" role in both uplink and downlink operations
   Provides knowledge of (i) uplink intent and (ii) autonomy required to perform downlink analysis
2. Develop and support algorithmic tools to *reconstruct what* happened and spacecraft *state*, and help users identify *relevant predicts* to compare actuals with.
   Reduce mental load for mechanical tasks, allowing operators to focus on identifying complex correlations
3. Build interfaces that allow users to build a *mental model* of autonomy decisions and *correlations* between states and decisions
4. Maximize *compatibility* with existing tools to foster adoption

Infusion Plans

National Aeronautics and Space Administration

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Publications:

Rossi, F. et al. Workflows, User Interfaces, and Algorithms for Operations of Autonomous Spacecraft. In *IEEE Aerospace Conference*, March 2023.

Castano, R. et al. Operating Deep Space Autonomous Spacecraft: Ground Processes and Tools for Operability and Trust. In *International Conference on Space Operations (SpaceOps)*, March 2023.

Candela, A. et al. Outcome Prediction and Explainability for Mission Operations of Autonomous Spacecraft. In *Workshop on Human-Aware and Explainable Planning (HAXP), International Conference on Automated Planning and Scheduling (ICAPS HAXP 2023)*, July 2023.

Castano, R. et al. Operations for Autonomous Spacecraft. In *IEEE Aerospace Conference*, March 2022.

Castano, R. et al Operations For Autonomous Spacecraft: Workflows And Tools For A Neptune Tour Case Study. In *Lunar and Planetary Science Conference (LPSC)*, March 2022.

Vaquero, T. S. et al. A Knowledge Engineering Framework for Mission Operations of Increasingly Autonomous Spacecraft. In *Workshop on Knowledge Engineering for Planning and scheduling (KEPS), International Conference on Automated Planning and Scheduling (ICAPS)*, June 2022.

Castano, R. et al. Operations for Autonomous Spacecraft: A Neptune Tour Case Study. In *Outer Planets Assessment Group (OPAG)*, March 2021. USRA

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