Information-Driven and Risk-Bounded Autonomy for Adaptive Science and Exploration

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Program: FY21 R&TD Topics Strategic Focus Area: Systems architecture

Objectives

We are developing execution capabilities for autonomous systems that ***make decisions and adapt their behavior to seek out the most high-value scientific information, while bounding risk of failure.***

Vision: endow spacecraft with "scientific curiosity" enabled by information-seeking capabilities, and tempered by situation-appropriate conservatism (risk-awareness).

Goal 1) develop and demonstrate information-seeking and risk-aware autonomous execution for a single spacecraft system (Year 1), and multi-spacecraft systems (Year 2).

Goal 2) develop an approach to architecting information-seeking autonomous systems, based on the experience gleaned from the Year 1 and Year 2 prototype efforts.

Background

Robotic spacecraft are "agents" that act on the behalf of the science community ("Scientist Avatars" in the JPL Strategic Technology Directions document).

Although JPL is making significant investments in various autonomy technologies, there is a gap in investment in system-level autonomy architectures.

Information-seeking autonomy is an innovation with potential for transformational impact on the way our spacecraft enable scientific discoveries,

- complementing traditional scientist-in-the-loop operations with appropriately-conservative onboard direction of science measurement activities (based on scientist-specified models).

Approach and Results

Demonstration mission context: science-driven asteroid family mission responsive to decadal science.

Year 1 focus: autonomously targeted flyby of 24 Themis by a small spacecraft ("Mothercraft"), informed by observations taken by the Mothercraft during its approach of the asteroid and by precursor flyby images taken by a "Daughtercraft" cubesat deployed by the Mothercraft during cruise/approach.

Key innovative features of our executive:

(i) It chooses an ***information-maximizing measurement strategy*** based on the environment and initial measurements, e.g., based on lower-resolution images taken by the Mothercraft on approach to the asteroid, we choose a set of crater observations taken by a gimbaled science camera during its flyby, to provide the highest value from a scientific perspective.

(ii) It ***takes various mission risks into account*** in planning and executing its activities, such as the risk of missing important science due to pointing uncertainty, particularly for more oblique off-nadir observational geometries.

(iii) It can ***flexibly adapt its strategy on-the-fly*** based on information from collected measurements, e.g., modifying the Mothercraft flyby observation plan to target the most promising craters based on additional information communicated by the Daughtercraft.

(iv) Finally, it demonstrates ***resilience in accomplishing its high-level science objectives***, even in the presence of failures/degradations, e.g., by using the policy to quickly modify the plan in response to missed observations of craters during the flyby, to optimize the scientific information return as much as possible for the remaining observations.

Accomplishments:

- Development of a mission architecture description and driving scenarios for the information-seeking autonomy capability. [Figure 1].
- Development of an information-seeking planner that optimally chooses craters to image during a flyby – implemented as an extension of MIT's Enterprise executive software. [Figures 2 & 3].
- Initial sketch of language constructs needed to specify risk-bounded information-theoretic planning problems – to implement in Year 2 as an extension of MIT's Reactive Model-based Programming Language (RMPL).
- Implementation of a basic spacecraft simulation capability (based on the Robot Operating System and the Basilisk open-source spacecraft simulation framework). [Figure 4]
- End-of-year demonstration of these capabilities executing in the asteroid mission context.

Significance/Benefits to JPL and NASA

Increased Science Return: By combining science operator-directed activities with autonomous science-driven exploration, our approach addresses biases associated with measurement selection. That is, we are endowing the spacecraft with common sense to avoid only visiting sites that are known to scientists and thus only add incremental science value (analogy: "looking for lost keys under the street lamp").

Greater Self-Reliance: By enabling spacecraft to respond to dynamic and uncertain environments autonomously, we decrease the average time needed to respond to off-nominal scenarios (by potentially as much as an order of magnitude), by significantly reducing the frequency of required downlink-uplink iterations.

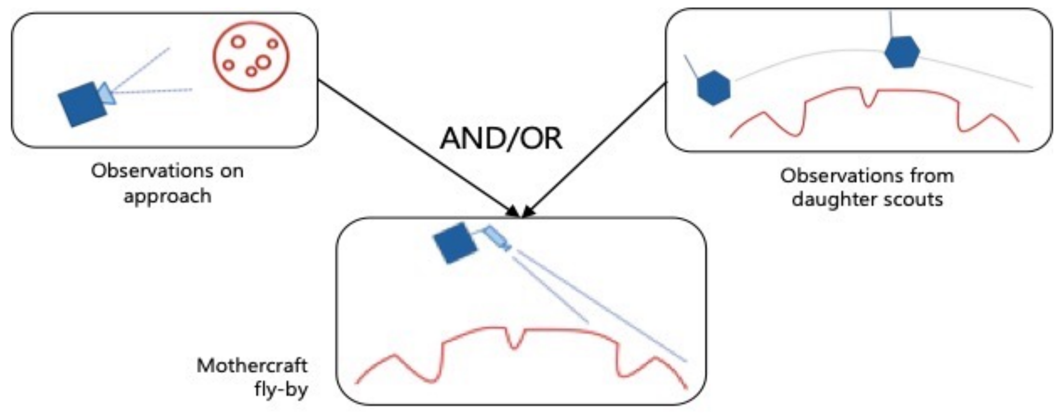

Figure 1. Asteroid Flyby Scenario.

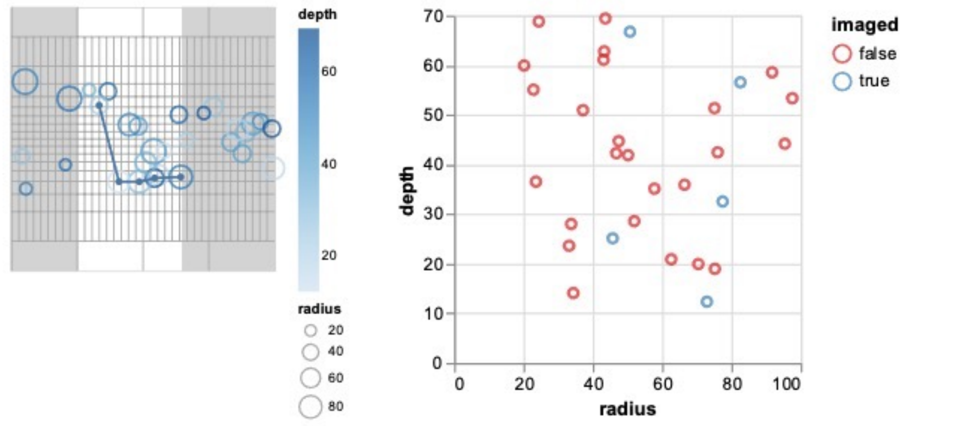

Figure 2. (L) Crater imaging sequence (flyby left-to-right) (R) Exec selects craters to optimize coverage of feature space.

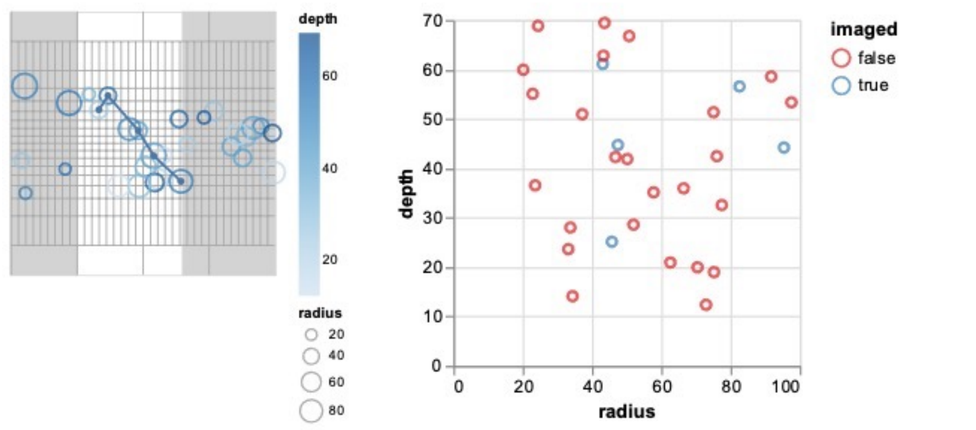

Figure 3. Results for lower camera slew rate limit. Different craters selected, while still maximizing feature coverage.

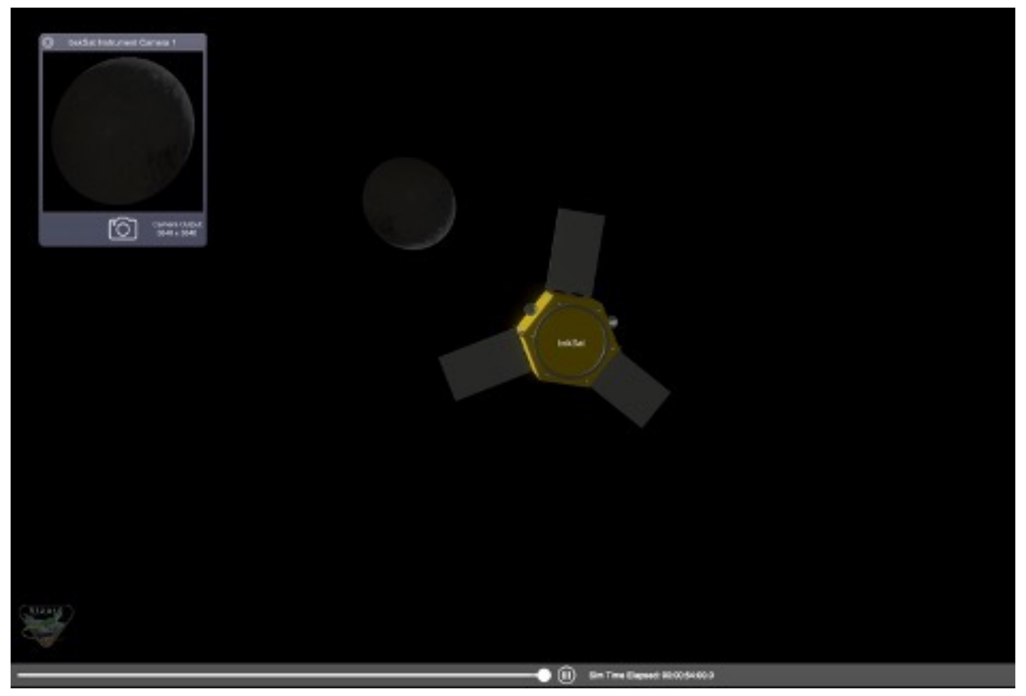

Figure 4. Basilisk simulation, showing moment on approach where Mothercraft images asteroid.

National Aeronautics and Space Administration

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California Institute of Technology
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Publications

[A] Ayton, B., Reeves, M., Timmons, E., Williams, B.C., and Ingham, M.D, "Toward Information-Driven and Risk-Bounded Autonomy for Adaptive Science and Exploration", *AIAA ASCEND 2020 Conference*, Virtual online, November 2020.

[B] Timmons, E., et al.,"Information-Driven and Risk-Bounded Autonomy for Scientist Avatars", *To appear, AIAA ASCEND 2021 Conference*, Las Vegas, NV, November 2021.

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