National Aeronautics and Space Administration

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

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Program: FY22 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.

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

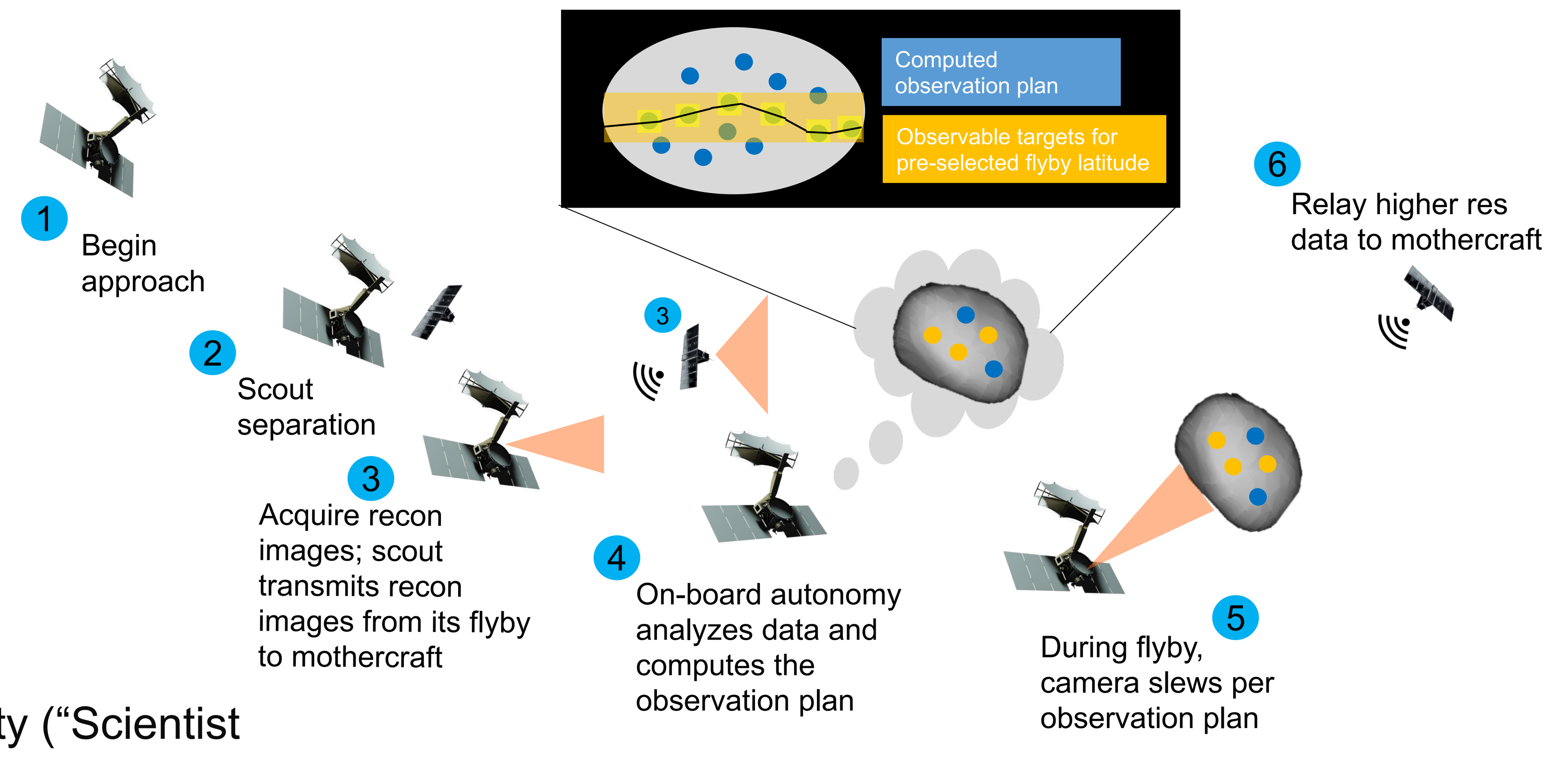

Figure 1. Asteroid Flyby Scenario.

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).

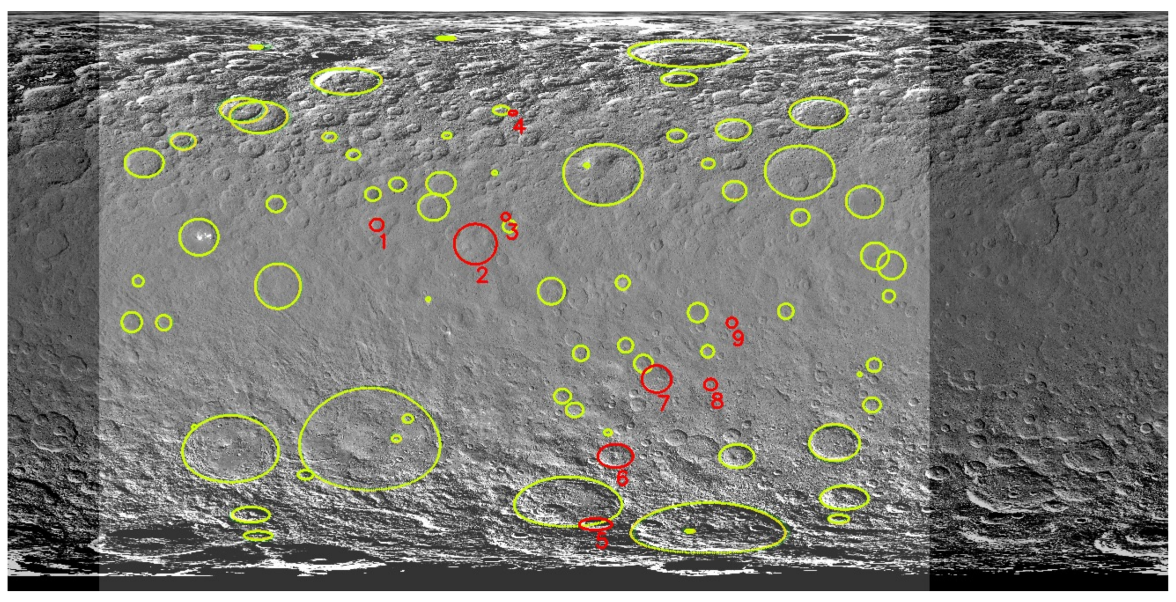

Figure 2. Map of asteroid showing full set of craters identified in recon imaging by Daughtercraft, and sequence of info-maximizing observations (in red).

Approach and Results

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

Year 1: autonomously targeted flyby of 24 Themis by a small spacecraft ("Mothercraft"), informed by observations taken during its approach of the asteroid.
Year 2: we factored in precursor flyby images taken by a "Daughtercraft" cubesat deployed by the Mothercraft during the cruise/approach phase.

Key innovative features of our executive:

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

(ii) It ***takes various mission risks into account*** in planning and executing activities, such as 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 Mothercraft flyby observation plan to target most promising craters based on additional information communicated by Daughtercraft.

(iv) Finally, it demonstrates ***resilience in accomplishing high-level science objectives***, even in presence of failures/degradations, e.g., by quickly modifying plan in response to missed observations of craters during flyby, to optimize scientific info return for remaining observations.

Accomplishments:

- Development of a mission architecture description and driving scenarios for the information-seeking autonomy capability (Figure 1).
- Specification of info-theoretic autonomy language as an extension of MIT's Reactive Model-Based Programming Language, and example applications of these constructs for selected asteroid mission scenario.
- Development of three alternative risk models for the selected asteroid mission scenario.
- Development of an information-seeking risk-aware planner that optimally chooses craters to image during a flyby – implemented as an extension of MIT's Enterprise executive software (Figure 2).
- Implementation of a spacecraft and environment simulation capability (based on Robot Operating System and Basilisk open-source sim framework).
- End-of-year demonstration of these capabilities executing in the asteroid mission context.
- Papers presented at AIAA ASCEND 2020 [A] and 2021 [B], and paper in work for ASCEND 2022 [C].

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 downlink-uplink iterations.

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www.nasa.gov

Clearance Number: CL#
Poster Number: RPC#

Publications:

[A] Ayton, B., et al., "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", AIAA ASCEND 2021 Conference, Las Vegas, NV, November 2021.

[C] Timmons, E., Williams, B.C., Ingham, M., Castillo-Rogez, J., Chung, S., Donitz, B., Havelund, K., Jasour, A., Mages, D., Rahmani, A., Seto, W., and Tavallali, P., "Autonomous Planning and Execution for Information-Driven, Risk-Bounded Scientist Avatars", To appear, AIAA ASCEND 2022 Conference, Las Vegas, NV, October 2022

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