Design Reference Mission (DRM) Scenarios for Small Bodies Enabled by Advances in Autonomy

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Introduction*:* Small Bodies, such as near-Earth objects (NEOs), comets, and asteroids, are abundant and diverse in their composition and origin. Exploring them is important for four thrusts: science, human exploration, *in-situ* resource utilization, and planetary defense. Operating near, on, or inside these bodies is challenging because of their largely unknown, highly-rugged topographies and because of the dynamic nature of the interaction between the spacecraft and the body. Furthermore, targets in the outer solar system, such as transneptunian objects, are outside reasonable telecom range for ground-in-the-loop operations that require rapid response to hazards and science discovery. Future missions would require autonomy to overcome these challenges and achieve effective mission operations. Many previous small-body missions have used some level of autonomy, but all operated within narrow windows and constraints. Autonomy will both enable missions to reach far more diverse bodies and enable greater access to those bodies than the current ground-in-the-loop exploration paradigm. NEOs are well-suited targets for advancing autonomy because they embody many of the challenges that would be representative of even more extreme destinations but are accessible by small affordable spacecraft [1][2].

Approach and Results*:* In October 2018, NASA's Science Mission Directorate organized an Autonomy Workshop [3] to examine the projected impact of autonomy across future science missions. Below, we summarize the findings reported by the Small-Bodies Working Group whose membership of scientists and engineers included leaders from academia, industry, and NASA centers. The group formulated two Design Reference Mission (DRM) scenarios: *(1) A mission from Earth's orbit to the surface of a Small Body:* This near-term scenario (launch in 2030s) seeks to reach a selected asteroid, approach and land on the body, precisely access at least one target on the surface, sample, analyze the measurements, retarget follow-on measurements based on local analyses, and send the results back to Earth—all of which would be done autonomously. *(2) Mother/daughter craft to understand the Small-Body population:* This long-term scenario (launch in 2040+) places a centralized mother platform with multiple daughter satellites in Earth's orbit to scan, identify, characterize, and eventually enable access to a range of NEOs leveraging technologies deployed by the near-term DRM. The mother craft would dispatch daughter craft to explore diverse bodies (including opportunistic visits to interstellar or hazardous objects). These daughter craft would visit the targets to collect samples and return material to the mother craft for further analysis or for resource extraction.

Required Autonomy Advances: These scenarios would require a level of autonomy that is not currently available. For the near-term DRM, these technologies include:

End-to-end, long-duration autonomy. Operating for a long duration in spite of unknowns, degradations, faults and failures is crucial. To date, autonomous capabilities have only been used for relatively short mission durations with pre- and often post-monitoring from the ground. These missions must be capable of establishing situational- and self-awareness and reasoning and acting under a wide range of conditions that include detecting faults and failures and mitigating the problem(s).

Approaching and landing on a body. During approach, an autonomous system must be able to observe, track and model the body's trajectory, rotation and shape from thousands of kilometers, when uncertainties are large, down to the surface to avoid collision. During this operation, it must also refine its knowledge of the spacecraft's motion and command its maneuvers. Using its onboard models, autonomy must be able to assess the hazards in the environment at the scale of the spacecraft in order to identify, avoid, guide and land the spacecraft at a safe location, while minimizing its consumption of resources. Today, such feats take months of human-intensive operations.

Handling the environment. With limited *a priori* knowledge of the environment, autonomy needs to handle large uncertainties that result from the irregular topography, low gravity, debris near the surface, and dynamic conditions that arise from outgassing or ejection of blocks or particles. The spacecraft must be able to monitor and react to such conditions in real time.

Proximity interaction. Autonomy must be able to handle physical interactions with an unknown environment. Exploration near, onto, or into the surface requires an understanding of the body's geophysical properties and the dynamic interaction between the spacecraft and the low-gravity body. Models have to be generated and actions taken in real time. Autonomy needs to adapt and learn from its operations.

Reaching specific surface targets. Autonomy must be able to establish situational awareness while on the surface, assess hazards for mobility, and plan and execute motions to reach multiple and specific destinations on the surface within specific timeframes and resources. Autonomy must continually localize the spacecraft on the surface and update its knowledge of the environment. Surface mobility would be highly stochastic due to large variations in topography and local gravity.

Manipulating the surface or subsurface. Autonomy is required for analyzing and identifying samples for collection and sample handling.

In addition to these autonomy capabilities, other technology advancements include propulsion ($\Delta V > 3$ km/s), onboard computing, sensing, mobility, communication and miniaturization.

For the long-term DRM, additional autonomy advances that are required include:

Extracting resources. Autonomy is required for anchoring or holding on to the surface and reaching deep into the body, which depends on instantaneous local conditions. It is also needed to support extraction and handling of large volumes of material for processing.

Detecting Small Bodies and coordinating multi-craft. Autonomy is needed to identify Small Bodies in space based on intent, then track and estimate their trajectories. It is also needed to plan cruise trajectories to the body, coordinate between the mother and daughters, and dispatch appropriate daughters to specific bodies. For long-term operations, autonomy is required for returning to the mother, docking and refueling.

Planetary defense. Planetary defense requires, first, understanding the composition and geotechnical properties of Small Bodies. Mitigation would require dealing with a largely unknown interior and surface. Both the understanding and mitigation would best be accomplished with autonomous spacecraft. Furthermore, several deflection scenarios, such as a kinetic impactor or gravity tractoring, require the spacecraft to navigate autonomously due to the need to adjust the trajectory in real time.

Like the near-term DRM, other technology advances include low-mass replenishable propulsion with $\Delta V > 5$ km/s, docking/undocking with the ability to transfer volatiles, large-scale surface mobility, subsurface excavation, material handling, and communication among multiple space-, surface-, and below-surface assets.

Investments in autonomy for Small-Body missions would provide NASA with far-reaching benefits. Implementing autonomy at NEOs will provide a "sandbox" for researching, developing, testing, and maturing technologies that can be used in more complex, less forgiving (motion is slower in the microgravity surrounding NEOs), and more expensive mission scenarios. Small-Body autonomy embodies challenges that are common to several other DRMs also under study for NASA:

- Unknown topography for mapping and characterization (most targets)
- *A priori* unknown surface properties (most targets)
- Extremely rugged surfaces such as the surfaces of Europa and Enceladus
- Operating in environments that pose dynamic hazards to a spacecraft such as winds, plumes, or active surface ejecta
- Obstructions to line-of-sight communications, in particular, when reaching into the subsurface (e.g., icy moon ocean exploration)

Next steps would include defining crisp engineering challenges to seed solicitations for developing and maturing the key autonomy technologies, coupled with high-fidelity end-to-end physics-based simulations to support that development.

References and Publications

[1] C. Mercer, "Small Satellite Missions for Planetary Science," 3rd Annual AIAA/USU Conference on Small Satellite, [2] S. Papais et al., "Architecture Trades for Accessing Small Bodies with an Autonomous Small Spacecraft," *AeroConf*, 2020, [3] https://science.nasa.gov/technology/2018-autonomy-workshop