NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

2018 Workshop on Autonomy for Future NASA Science Missions: Small Bodies Design Reference Mission Reports

Table of Contents

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

Introduction

Autonomy is changing our world; commercial enterprises and academic institutions are developing and deploying drones, robots, self-driving vehicles and other autonomous capabilities to great effect here on Earth. Autonomous technologies will also play a critical and enabling role in future NASA science missions, and the Agency requires a specific strategy to leverage these advances and infuse them into its missions. To address this need, NASA sponsored the 2018 Workshop on Autonomy for NASA Science Missions, held at Carnegie Mellon University, October 10-11, 2018.

The Workshop goals included:

- Identifying emerging autonomy technologies (10-15 years) that will:
    - Enable or enhance mission capabilities
    - Reduce risk
    - Reduce cost
- Identifying potential collaborations, partnerships, or linkages involving government, industry, and/or academia to enable these technologies

Capturing crosscutting autonomy technology requirements for future NASA missions
Over 90 individuals from industry, academia, and NASA participated in the workshop, which included presentations by keynote speakers, panel discussions, and small group discussions.

To provide structure for workshop discussions and post-workshop analysis, NASA established eight teams to examine the following Design Reference Mission (DRM) areas: Astrophysics, Earth Science, Heliophysics, Mars, Moon, Ocean Worlds, Small Bodies and Venus. Each DRM team was led by a scientist and a technologist, and team members consisted of workshop participants with relevant experience and interest. NASA asked each team to develop one or more mission scenarios that would be enabled by infusion of autonomous technology. The Agency provided guidance to support these team discussions; in particular, NASA urged the DRM teams to "think out of the box" and to consider bold missions that would be enabled by autonomous technology to provide valuable science results. Each DRM team developed mission scenarios that included defined science objectives, capability and technology needs, system requirements, and a concept of operations. Teams also identified gaps where autonomy technologies and other supporting technologies need to be developed and/or infused to enable each mission.

The DRM teams conducted small group discussions at the workshop and then presented a summary of their findings to all workshop attendees. Each DRM team continued to refine its mission scenarios after the workshop, creating both a full report and a summary report to document team findings. DRM teams also reported results at the December 2019 meeting of the American Geophysical Union.

This document contains the full report and summary report generated by the Small Bodies DRM team. Full and summary reports generated by all eight DRM teams, plus a summary of workshop results are available online.

Small Bodies Design Reference Mission Report

Part I: Summary

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 to advance knowledge in four "thrusts:" decadal science, human exploration, in situ resource utilization (ISRU), and planetary defense. Small Bodies are found all across the solar system and up to the Oort Cloud. Advancements in the aforementioned thrusts depend on: (1) knowing what is where, (2) characterizing the bodies' compositions, (3) understanding their geophysical (including geotechnical) properties, and (4) characterizing their environments.

Autonomy is enabling for Small Body missions because it would allow greater access and enable missions to reach far more diverse bodies than the current ground-in-the-loop exploration paradigm. 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. These challenges require autonomy for effective mission operations. Most Small Body missions have used some level of autonomy, but all operated within narrow windows and constraints.

Small Bodies are well-suited targets for advancing autonomy because they embody many of the challenges that are representative of even more extreme destinations, but are accessible by small affordable spacecraft (e.g., SmallSats). Small Bodies are abundant, diverse, and many are within reach to enable a string of missions that not only serve to advance autonomy but are also of inherent value to advance the aforementioned thrusts. Given their diversity, Small Body environments would be unknown a priori and the interaction of a spacecraft near or onto these surfaces would be dynamic for the low-gravity bodies. Technologies developed for autonomous exploration of Small Bodies would have high "feedforward" potential to enable more challenging exploration efforts such as an aerial explorer that canvasses Titan's terrains, dips into its liquid lakes, or sends probes into its ocean-world interior; or an explorer that samples the plumes of Enceladus' Tiger Stripes; or an explorer that ventures into crevasses of Europa, to name a few.

Design Reference Missions

The goal of this Design Reference Mission (DRM) team is to use autonomy to change the paradigm of exploring Small Bodies to one that *enables access to a large number of diverse bodies at affordable cost with minimal human intervention.* The team defined two bold DRMs that autonomy would enable and for which Small Bodies would offer a compelling target for technological advances.

1. **DRM 1: A mission from Earth's orbit to the surface of a Small Body.** This near-term DRM, envisioned for a ~2030 launch, places an affordable SmallSat in an Earth orbit or

at Earth-Sun L1 with the high-level goal of reaching a selected asteroid, approaching, landing, accessing a targeted destination, sampling, analyzing the data to target follow-on measurements, and communicating the results of the full investigation back to Earth—all of which would be done autonomously. In essence, demonstration of autonomous exploration capabilities for NEOs would help enable the exploration of other populations such as Trojan asteroids and Kuiper Belt objects (KBOs).

2. **DRM 2: Mother/daughter craft to understand Small Body population.** This long-term DRM**,** envisioned for the 2040s, substantially expands the scope of the first DRM to achieve the goal of the cursory exploration of the entire population of Small Bodies, or at least a large enough sample to have confidence that it is representative. It features a mother/daughter architecture of satellites in Earth's orbit to scan, identify, characterize, and eventually enable access to a range of Small Bodies. The mother craft would dispatch daughter craft to explore diverse bodies (including opportunistic visits to interstellar objects 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. The mission would also be capable of diverting potentially hazardous asteroids, if necessary.

Comparison to State of the Art

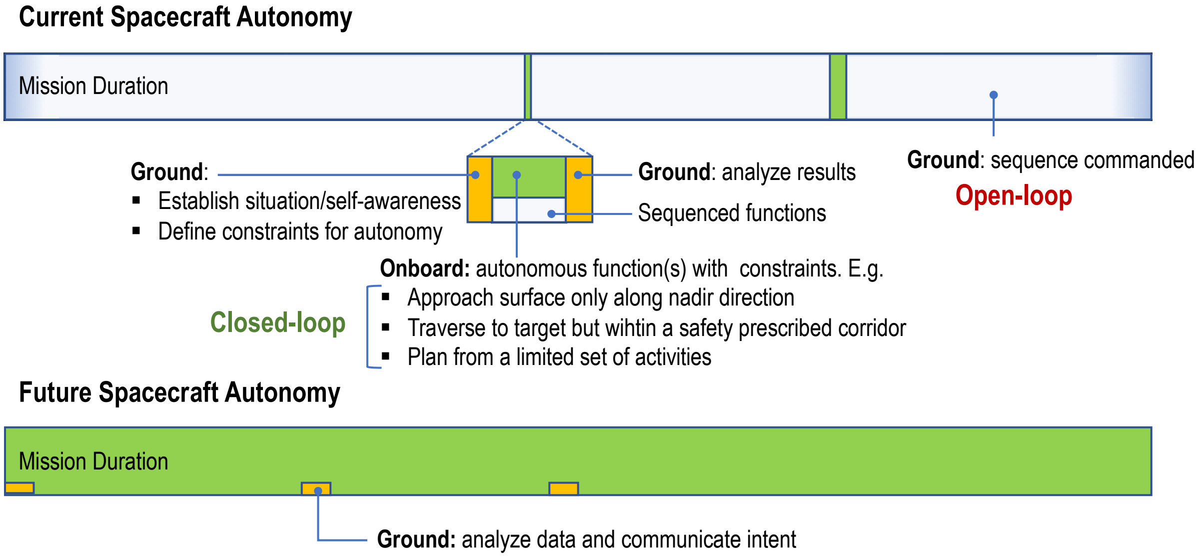

***Figure 1**: Spacecraft autonomy today and in the future*

Building up a fully autonomous capability to access and operate on Small Bodies is a paradigm shift from the current approach, several elements of which are accomplished with some autonomous capability. Examples of autonomous functions for Small Bodies include: autonomous navigation for short durations, elements of fault management, and limited untargeted autonomous surface mobility (Figure 1). With the current practice of deploying one expensive mission at a time through carefully pre-planned explorations, the pace of exploration will remain modest. However, deploying highly autonomous spacecraft, together with advances in spacecraft bus technology (propulsion, computing, sensing) would expand access to Small Bodies. These DRMs aim at bold, yet measurable and fieldable, advances to facilitate the paradigm shift.

Critical Autonomy Technologies for DRM 1

Situation-awareness **Self-awareness** **Reasoning and Acting**

- Spacecraft **guidance** and **navigation** with trajectory correction maneuvers
- Unknown body rotation, shape, and gravity **estimation** during approach
- **Hazard assessment** (debris or orbiting moons) near and on the body (gas vents, rough topography, boulders) for safe and precise landing
- Surface, and possibly interior*,* **composition characterization** and **regolith property characterization** for mobility and sampling
- Landing **site selection** based on safety and value for investigation
- Proximity-maneuver **planning and control** for landing
- Surface **mapping**, **hazard assessment,** and **mobility** to selected targets
- Shallow **manipulation** of unknown/rugged surface for measurements
- Spacecraft **health management** throughout all phases
- **Spectral data analysis** assessing quality and interpreting data; **selection** of future measurements and targets; **calibration, pointing, and placement** of instruments; **returning results** to Earth (through all phases)

Supporting Technologies for DRM 1

The key supporting technologies to achieve the near-term DRM are:

1. **SmallSat** propulsion with $\Delta V > 1{,}000$ m/s[1] (excluding Earth escape velocity)
2. **Advanced onboard computing and storage:** low-power, low-mass, high-throughput computing with specialized processing for computer vision and possibly neural networks for machine learning to enhance predictive models of the environment
3. **Advanced sensing and optics:** low-power, low-mass, high-resolution miniaturized cameras with variable zoom optics and spectrometers
4. **Surface mobility** and **subsurface mechanisms**
5. **Communication:** low-mass, low-power, direct-to-Earth communication from SmallSats

Findings regarding DRM 1

To realize this vision, this DRM team recommends the following actions:

1. Establish a one-year project with participation from NASA/industry/academia *to flesh out the design details, assess the applicability of external technologies* (automotive and logistics industries/government agencies) *and identify detailed gaps, provide specification for supporting technologies* including rapid systems engineering, and estimate cost of developing and verification and validation (V&V) of the various capabilities.
2. Define crisp engineering challenges to seed solicitations for:

---

[1] Based on preliminary analysis of accessible known targets, there are over 600 bodies that would require $\Delta V < 1{,}000$ m/s to reach

   - Developing a high-fidelity, end-to-end, physics-based simulation to support the development of a fully autonomous mission to a Small Body using SmallSats.
   - Developing and maturing the key autonomy technologies using the full lifecycle simulation.
3. Establish a project to integrate hardware and software capabilities, test them in simulation, and mature them for flight demonstration
4. Demonstrate capabilities of increased sophistication through a couple of SmallSat missions and/or extended missions of opportunity

Success Metrics for DRM 1:

A program to achieve the near-term DRM initially in simulation and later through flight missions could involve the following metrics:

- A SmallSat mission with ΔV of 0.8 – 1 km/s that launches, cruises, and reaches (fly by and images) a small body destination without ground-in-the-loop
- Ability to autonomously approach, rendezvous (ΔV of 5 – 10 km/s) and map a Small Body
- Ability to select a landing site and land
- Ability to transform the approaching craft to a surface mobile platform or deploy a mobile asset and collect samples
- Ability to analyze spectral data to drive future sampling and resource extraction

Value to NASA:

Space exploration is an endeavor with numerous challenges and constraints. Autonomy could prove to be a pivotal technology that establishes a new paradigm of exploration. To usher in this new era, a systematic and focused approach is needed for a sustained development program to overcome the multitude of challenges. As such, it is critical for the program to be affordable and with easy-to-evaluate success-milestones. Not only would these technologies advance the Small Body thrusts, they would have strong “feedforward” benefit for missions to more challenging and remote planetary destinations including visiting a nearby exoplanetary system. Some of NASA’s challenges remain unique, e.g., venturing into unknown and bizarre worlds with no a priori data to learn from and with no opportunity to change the design or fix the craft once launched. However, a vast array of technological advances exists today at NASA and in industry that could help NASA advance its mission. The challenge lies in properly architecting the spacecraft of the future and in closing these technical gaps.

Supplemental Information: DRM 2, Long-term (2040+ DRM)

Critical Autonomy Technologies for DRM 2

Situation-awareness **Self-awareness** **Reasoning and Acting**

- All technologies for DRM 1 +
- Onboard **identification**, tracking and **trajectory estimation** of Small Bodies **based on intent**
- **Trajectory planning** for heterogenous daughter craft

- **Multi-craft coordination**
- Large-scale **manipulation** of **unknown material**
- **Resource extraction**
- **Rendezvous** and **docking** with mother craft **and refueling**

Findings regarding DRM 2

The Small Bodies DRM team finds that the following actions and activities would facilitate implementation of DRM 2.

1. Hold off on DRM 2 until substantial progress is demonstrated under DRM 1 (DRM 2 fully subsumes DRM 1)
2. Following demonstrated in-space capabilities of DRM 1, start fleshing out the details of DRM 2 based on technologies at the time
3. Define concrete plans for ISRU and planetary defense
4. Work with academia to advance fundamental technologies and with industry to mature technologies and realize them in flight
5. Establish these important capabilities for the safety (diverting bodies) and knowledge (science and human exploration) of the Nation and the world

Success Metrics for DRM 2:

For the long-term DRM (2040+), a larger craft with ΔV of 1 – 10 km/s would be able to reach farther destinations and handle larger amount of material. DRM 2 would involve all of the success metrics for DRM 1, plus the following:

- Ability to access well below surface
- Ability to extract resources
- Ability to adequately alter the trajectory of a body for planetary defense purposes
- Ability to fly through and sample a plume on a comet

Part II: The Case for Small Bodies

Introduction

Small bodies comprise many types including near-Earth objects (NEOs), short- and long-period comets, main-belt asteroids, Jovian Trojans, trans-Neptunian objects, and more. These objects are numerous[2] and varied in terms of *location*, *composition*, and *physical properties*. Therefore, when discussing and developing potential Design Reference Missions (DRMs), the Small Bodies DRM team concentrated on the issues that potential Small Body missions have in common.

Why Small Bodies?

Small bodies are valuable targets for:

- decadal science,
- human exploration,
- in situ resource utilization by the public and private sectors, and for
- planetary defense.

Although several missions have focused, or will focus, on Small Bodies, these objects are so numerous and so diverse that they can be used to address a wide range of topics. The objects range from volatile-rich comets that are likely remnants of planetary formation to metal-rich asteroids that are likely the remnants of the cores of planetesimals. Small Body locations range from Earth-crossing orbits, where they are simultaneously attractive targets for resource utilization and potential hazards from a planetary defense perspective; to objects like Centaurs and Jupiter Trojans, whose orbits suggest that they hold keys to the early dynamical history of the solar system; to trans-Neptunian objects that are likely to hold clues to the formation of the outer planets. The objectives of Small Body research include obtaining the following information:

Table 1. Science Objectives

Objectives	State of the Art
What is where: the locations of the various bodies can inform us about a. the origin of the solar system: how did it form?	Current knowledge of the architecture of the solar system is primarily derived from surveys using ground-based telescopes, with some space-based surveys, most notably the NEOWISE program (Wide-field Infrared Survey Explorer [WISE] extended mission). The Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer (OSIRIS-Rex) mission was the first

---

[2] For example, there are approximately 800,000 numbered asteroids alone.

Objectives	**State of the Art**
b. the architecture of the solar system: how did it end up in its current state?	spacecraft to try to survey a region poorly accessible from Earth, searching for Earth Trojans while passing near the Earth's L4 Lagrange point[3]. Although none were found, other regions, including planetary Trojans, irregular satellites of giant planets, and even Kuiper Belt Objects, could best be searched by nearby spacecraft that are autonomous enough to conduct the kind of survey that is now done with humans in the loop[4].
Composition of the body: volatiles like water–a precursor to life on Earth (not looking for life on Small Bodies, but for the source of such molecules) a. Astrobiology b. Formation c. Resources (the most valuable, the least complex to extract)	For most Small Bodies, if there is any compositional information, it comes from spectroscopy, usually infrared, which can be used to detect molecules (for comets) and minerals (for asteroids). In most cases, the spectroscopy is ground-based, although some spacecraft missions, most notably Rosetta, Dawn, and OSIRIS-REx, have also carried spectrometers. In some cases, such as Near Earth Asteroid Rendezvous (NEAR) Shoemaker at Eros and Dawn at Vesta and Ceres, missions have used gamma-ray and neutron spectroscopy to determine major element composition. For trace elements, knowledge is limited to returned samples and to inferences from meteorites that are matched, with varied degrees of confidence, to particular asteroids or types of asteroids.
Geophysical properties of the body a. Current and past processes b. Interaction (crewed and robotic) with and stability of the surface	Knowledge of geophysical properties is extremely limited. In a few cases (NEAR Shoemaker, Hayabusa, Hayabusa2, Rosetta, and soon OSIRIS-REx), a spacecraft has either touched a surface or has deployed a lander, but the geotechnical information has been only a byproduct of studying the interaction, rather than the result of dedicated studies. Bulk properties, such as density and porosity, can be inferred from missions that spend extended periods of time near small bodies, but even then, it cannot be determined whether the porosity is at a macroscopic or microscopic scale. Properties such as

---

[3] S. Cambioni et al. (2018) *49th Lunar and Planetary Science Conference*, Abstract #1149.

[4] New Horizons spacecraft has conducted searches for KBOs in that vicinity

Objectives	State of the Art
	cohesiveness have never been studied, except to the extent that meteorites serve as analogs.
Characterizing the environment a. Atmospheres, particles, and fields (includes outgassing) b. Potential presence of hazards for crewed and robotic missions c. Spatial and temporal temperature distribution d. Radiation	Small Bodies environments vary wildly. Knowledge of atmospheres comes in large part from spectroscopy. Cometary bodies offer all types of environmental challenges, including the ejection of meter-sized blocks. Airless bodies, especially Small Bodies, may be surrounded by dust ejected by micrometeorites and/or regularly lofted as a consequence of electrostatic charging. These factors may represent potential hazards and require characterization during approach. Thermal mapping from orbit is needed for landing site selection (both from an energy management standpoint and for inferring regolith structure for landing and mobility).

What Small Bodies?

The particular mission goals determine the appropriate type and size of the body to target. The size of Small Bodies can span meters to several thousand kilometers. In this Small Bodies DRM team, our focus is on bodies that range from meters to only tens of kilometers in size, where there is just enough gravity[5] to make operations on the surface particularly challenging: enough gravity that its effects have to be considered in maneuvering and operating, but not enough gravity to be able to remain in a safe orbit for extended periods of time without actively adjusting and monitoring location and not enough gravity to safely anchor to the surface of the body. Missions to larger and more remote bodies, such as Pluto and Ceres, would still benefit from many of these technologies, but would need further advances to enable more timely response dictated by the higher gravity and challenging topographies. Additional technologies for such bodies are also addressed by the Ocean Worlds DRM team.

Table 2: Highlights of autonomy advances across Small Body missions (past and current)

	Demonstrated Autonomy Advance	Capability/ Technology	Key Gaps and Needed Capabilities

---

[5] For bodies of meters to tens of kilometers gravity can range from 10^{-6}g – 10^{-3}g

1998 – 2001 Deep Space I	Cruised autonomously for 3 of 36 months (<10%); 30-minute autonomous flyby	Planning/scheduling Autonomous navigation (asteroid detection, orbit update, spacecraft low-thrust Trajectory Correction Maneuvers or TCMs) System health management	**Key Gaps** ▪ **Limited scope of autonomy use:** capabilities have only been used for relatively short durations of the mission with pre- and sometimes post-monitoring from ground. ▪ **Use of a priori maps:** missions with proximity operations required extensive ground processing to generate maps that were used in subsequent autonomous maneuvers. ▪ **Reliance on ground-based resource planning** **Needed Capabilities** ▪ End-to-end, long-duration autonomy ▪ Autonomy in light of faults and failures ▪ Autonomy in environments with large uncertainties and limited a priori knowledge of the environment ▪ Autonomy that can handle a wide range of conditions, adapt and learn from its operations
2002– 2011 Stardust	30-minute autonomous flyby of one asteroid and two comets	Target-body detection (one body) Attitude updates for tracking nucleus through flyby	
2005 – 2010 Deep Impact	Two-hour autonomous terminal guidance of comet impactor Flyby tracking of two comets	Target-body detection (one body), orbit update, and spacecraft low-thrust TCMs	
2005 Hayabusa	Autonomous terminal descent of last 50 m toward a near-surface goal for sample collection	Laser ranging (at < 100m) to adjust altitude and attitude	
2019 Hayabusa2	Same as Hayabusa	Same as Hayabusa; bright surface object detection and centroiding; hybrid ground/onboard terminal descent control: ground controls boresight approach, while onboard controls lateral motion in final 50 m; on surface, open-loop control of surface hopping mobility	
2020 OSIRIS-REx	Potential plan: terrain-relative navigation (TRN) for touch-and-go maneuver	Uses ground-generated shape-model, match natural features to model using TRN with ground oversight; onboard final maneuvers to initiate touch-and-go for sample collection	

2022 Double Asteroid Redirection Test (DART)	Several hours of autonomous terminal guidance (similar to Deep Impact)	Identification of each body for target selection; thruster control to guidance impact; targeting the 170-m moon of a 780-m primary	

Autonomy in current and planned missions to Small Bodies

To date, only five missions have attempted to operate for extended periods of time in close proximity to such Small Bodies: Shoemaker, Rosetta, Hayabusa, Hayabusa2, and OSIRIS-REx. The difficulties encountered by Rosetta's Philae lander and by the first Hayabusa mission highlight how much we do not know about these bodies. Most of these missions relied (or will rely) on autonomy to some degree, because of the obvious challenge of operating on or near a poorly understood surface at a distance of even a few light-minutes from Earth. Given the diversity of Small Bodies, it is likely that many more missions will have to be flown before we are likely to have experienced the range of surface properties we might encounter.

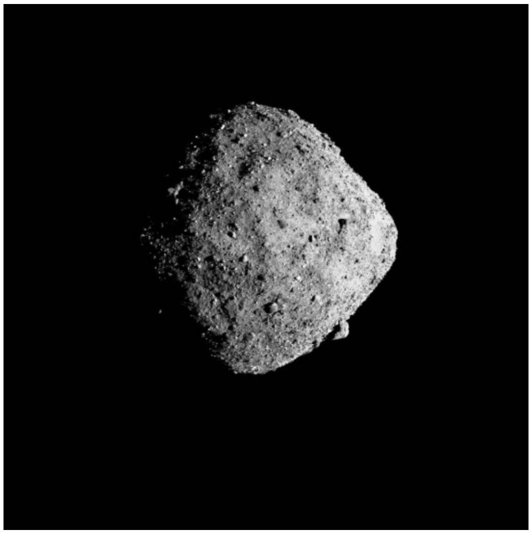

Figure 2: *Bennu, as imaged by OSIRIS-REx (NASA, Goddard Space Flight Center, University of Arizona). Note the large number of boulders.*

In addition, there have been numerous missions that have performed flybys of Small Bodies, beginning with the flyby of Halley's comet in 1986, followed by the Galileo mission's flyby of Gaspra in 1991. In many cases, such flybys have been en route to other mission targets, and the spacecraft have not attempted close flybys. But in some cases, most notably the recent New Horizons flybys of Pluto and 2014 MU$_{69}$ and the upcoming Lucy flybys of Jupiter Trojans, the flyby is the heart of the mission, and occurs at high velocity at a relatively large light travel time from Earth. New Horizons did not use autonomy for its flybys, and the decision for Lucy has yet to be made. However, it is clear that in cases like these, spacecraft with the capability to autonomously acquire the target object and manage both the nominal trajectory and the complications that could arise from previously unknown natural satellites or debris in the vicinity of the target, would enable better-targeted and closer approaches, yielding higher-resolution data.

Why is autonomy enabling for Small Body missions?

The limited use of autonomy has already proven essential for current missions to Small Bodies, in particular, for fast flybys and touch and go (TAG) for sample collection. More capable autonomy will make it possible to reach and explore a wider range of diverse bodies, conduct more in-depth investigations of their heterogeneous compositions, and develop a better understanding of their origins. Autonomy is enabling for small bodies because they are:

1. **Abundant and Diverse:** There are numerous and diverse destination options and autonomy would enable more access and exploration of these disparate and diverse bodies. As of early 2019, there are approximately 800,000 known asteroids, more than 2,000 Kuiper Belt Objects, and various other populations of Small Bodies. These objects can be classified by telescopic observations into groups that are almost certainly chemically distinct. Furthermore, even among bodies that are genetically related, there may be intact planetesimals, differentiated interiors, disruption fragments, and rubble-piles of reaccreted material, all representing different sets of processes. Hence, the number of different histories experienced by Small Bodies and the number of different pieces of solar system history accessible to study is extremely large among known Small Bodies. While it is easily possible to develop a mission to a single body, exploring this diverse population can be done most rapidly by employing many spacecraft, each of which can explore multiple bodies. With an eventuality of numerous spacecraft exploring numerous destinations and given limited communication windows, such assets would have to rely on onboard decision-making for local (within a body) and remote (other bodies) situations, evolving the role of ground control to the higher-level management of the parallel missions.
2. **Operationally Challenging:** Small Bodies have very rugged topographies with unknown surface compositions and a priori unresolved rotation and gravity parameters. The interactions of a spacecraft in proximity[6] of a Small Body, on its surface, or below its surface, all require resolving the body's motion parameters, understanding its non-uniform surface composition and gravity, and understanding its interior formation. Autonomy would enable:

---

[6] Interactions near (within ~50 m), on or into the surface are particularly challenging due to low gravity, surface roughness, and the dynamic nature of the interaction

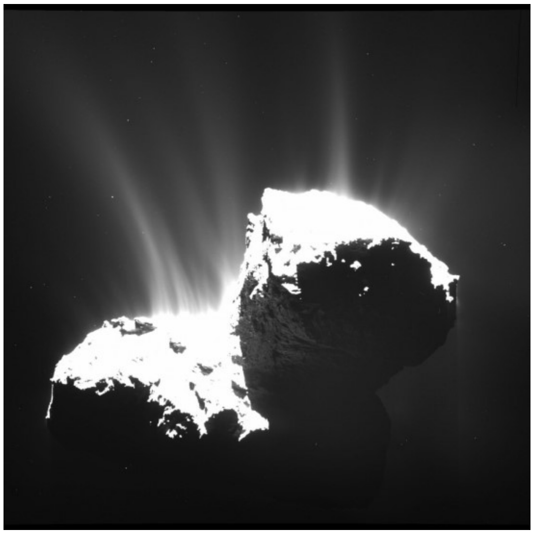

Figure 3*: Rosetta image of Comet 67P/ Churymov-Gerasimenko, showing material venting from surface (ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA /UPM/DASP/IDA)*

a. **Proximity Interaction:** Exploration near, onto, or into the surface requires an understanding of the dynamic interaction between a spacecraft and the a priori unknown low-gravity body. Autonomy would enable such dynamic interaction where models would have to be generated and reasoned about and where decisions would have to be made in real time[7]. These scenarios include final-descent phase of a spacecraft onto a Small Body, interaction with the body to understand its surface properties for both science or engineering purposes, or managing a robotic mechanism for mobility or sampling.
b. **Handling the environment:** In addition to the challenges of the irregular topography and low-gravity environment, some Small Bodies, such as comets, generate dynamic conditions from outgassing or block-ejection events (e.g., images of Hartley 2 during the EPOXI flyby revealed meter-sized ice blocks being ejected). Such conditions have to be monitored and avoided in real time.
c. **Reaching specific surface targets:** Reaching multiple and specific destinations on the surface of Small Bodies within specific timeframes is unlikely to be possible without autonomy. Reaching larger numbers of objects likely means accessing smaller objects, many of which may not be visible from Earth, and thus their basic physical properties may not be available to support an in situ mission. These destinations can be either densely or sparsely specified and can be targeted for measurement during specific time windows. Accessing the surface, whether to make seismic or ground-penetrating radar measurements of an asteroid, to approach a vent of a comet, or to sample any of these bodies, would require an interaction that cannot be reliably planned a priori.
d. **Manipulating the surface or subsurface:** Autonomy is required for resolving sample properties for collection (e.g., grain size) and for anchoring or holding onto the surface, which is based on instantaneous local conditions.
e. **Extracting resources:** Exploration in search of resources would likely require anchoring to and reaching meters below the surface. Extraction would require deeper access.

---

[7] The paradigm of planning actions of a spacecraft days or weeks in advance—while highly successful for flyby or orbiting missions due to ability to predict based on orbital dynamics—starts breaking down when interacting with an unknown environment, where models of such interactions are not available. Even the quasi-static surface exploration of Mars and the Moon have shown that for effective mobility, maneuvering and interacting with the surface, autonomy has become increasingly critical.

Such interaction would require reacting to local conditions to ensure proper grasp and effective extraction while handling anomalies due to interacting in a granular media environment.

   f. **Planetary defense:** Planetary defense requires understanding the composition and geotechnical properties of Small Bodies. Mitigation would require dealing with a largely unknown interior and surface that would best be approached 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.

3. **Enabled by Agile and Opportunistic Spacecraft:** Because of the wide array of sizes, locations and properties, large-scale exploration of Small Bodies can be achieved far more efficiently with a fleet of spacecraft. Each spacecraft could have limited capabilities but could be retargeted multiple times. Furthermore, such spacecraft might be retargeted to objects whose existence was not known at the time of launch.

A. Why are Small Bodies suitable targets for advancing autonomy?

Small Bodies, in particular NEOs, are well suited to advance autonomy because they embody many important attributes and challenges to overcome that are representative of bodies that are more distant. Small Bodies are suited to advance autonomy because they are:

1. **Abundant, Accessible and Affordable to Explore:** There are numerous nearby Small Bodies that can be reached with small and affordable spacecraft. Given their abundance and proximity to Earth, Small Bodies offer frequent yearly launch opportunities. Once outside Earth's gravity well, spacecraft can fly by one of hundreds of Small-Bodies by using ΔVs of less than 1 km/s and rendezvous with one using ΔVs of less than 5–10 km/s. Given their low gravity, Small Body surfaces can be reachable with low-power landing systems for trajectories with low-enough approach velocity. Descending on Small Body surfaces can be relatively slow and is unencumbered by the presence of an atmosphere that introduces additional uncertainty. The ability to use small spacecraft to reach Small Bodies and their surfaces make such objects affordable targets for both advancing the technologies and reaping the scientific and commercial benefits. There are approximately 20,000 Near Earth Objects[8] (NEOs); most are asteroids, but some are comets. There is currently no available database listing potential one-way missions[9] to NEOs, but a database for round-trip missions (https://cneos.jpl.nasa.gov/nhats/) lists more than 250 objects for which a round trip could be accomplished with a total ΔV from Earth orbit of less than 6 km/sec and a round trip of less than 450 days, without considering mid-course corrections, gravity assists, or continuous thrusting (e.g., electric propulsion).

---

[8] NEOs are small Solar System bodies with orbits around the Sun that are, at some point, between 0.983 and 1.3 astronomical units from the Sun. NEOs are not necessarily currently near Earth, but their orbits can potentially become Earth-crossing.

[9] A database for one-way missions is in development for access by robotics missions

2. **Scalable:** Small Bodies' accessibility and affordability lend them to missions that employ multiple spacecraft and spacecraft that can reach multiple destinations.

3. **Adequately challenging:** Small Bodies offer a unique balance between the a priori unknown environment and a low-gravity environment that drives a dynamic interaction with that body; the slow dynamics result in a more forgiving environment that minimizes the severity of impact with the surface. As such, Small Bodies offer a stepping stone toward the more complex dynamic of landing on larger bodies with largely unknown atmospheres.

Although the primary DRM discussed below is for a mission to a NEO, the autonomy technology needed would be enabling for missions to other Small Bodies. In particular, the more distant an object is from Earth, the longer the light-travel time for commands and data to move back and forth, and the more autonomous systems will enhance the mission. Safe near-surface navigation is critical for any mission involving a lander or rover, but that can only be done with autonomy due to the low gravity and the dynamic Small Body environment. And the more capable the autonomy, the more difficult (and more interesting) the target landing site can be. Once a mission lands or anchors on a Small Body, safe operations while moving, or while manipulating the surface or near-subsurface, can only be done very slowly, if at all, without autonomy. Even for less complex flyby missions, autonomy will make it possible to target closer flybys, by providing a means to search for and mitigate or avoid hazards in the form of moons, vents, etc.

Advancing autonomy for Small Bodies would advance and prove in-flight capabilities that could be used for other mission scenarios, such as the aerial exploration of Titan or Venus or the surface exploration of Enceladus and the sampling of its active plumes.

Part III: Design Reference Missions

The Small Bodies team developed two DRMs: (1) a relatively near-term DRM that could be accomplished in the 2030s timeframe and a (2) futuristic long-term DRM that would unlikely be accomplished before the 2040s. The ultimate goal is to accomplish a cursory exploration of the entire population of Small Bodies, or at least a large enough sample to be representative, and the futuristic DRM lays out a scenario to accomplish such a formidable challenge. The futuristic DRM subsumes the near-term DRM and expands its scope. This report primarily concentrates on detailing the near-term 2030 DRM, in keeping with the purpose of the NASA 2018 Workshop on Autonomy, and will only briefly touch upon the long-term DRM.

Autonomy is needed for both DRMs for the following reasons:

- To interact near (50-meters), on, or delve into the body's surface (e.g., for final descent, to understand surface properties, to manage a robotic mechanism to achieve mobility and interaction)
- To react to the dynamic environment conditions
- To access specific destinations in specific time frames and target areas for sampling and analysis
- For manipulation: to resolve sample properties in real time and react dynamically to surface conditions
- To collect samples (e.g., operating near a vent on a comet)
- To learn more about ISRU (will likely need to explore below the surface and possibly extract)
- For planetary defense: to understand the threat and how to interact with the Small Body

In addition, autonomy will enable scalability (the ability to explore numerous different destinations at multiple times or even simultaneously) through reduced costs, and agility (the ability to rapidly access various Small Bodies).

DRM 1: A mission from Earth's orbit to the surface of a Small Body

Synopsis: The mission places an affordable SmallSat in Earth's orbit with a high-level goal of reaching a selected asteroid, approaching, landing on the body, precisely accessing at least one target on the surface, sampling, analyzing the measurements, retargeting follow-on measurements based on local analyses, and sending the publication[10] back to Earth, all of which would be done autonomously.

Benefits: The benefits include addressing the science objectives in Table 1 and contributing information that informs planetary defense and in situ resource utilization. For planetary

---

[10] While the comment about autonomously producing the publication is said "tongue-in-cheek," the goal would be to produce data of the quality expected of publishable results, enabling explorers to focus on higher-order goals.

defense, such a mission could assess the threat to Earth (determining position, mass, properties of the body) and inform any mitigation strategies (e.g., how will the body react when we try to move it?). For ISRU, it would determine whether the body contains any resources of interest and how they could be accessed.

Related Work: Similar missions have been proposed or studied in the past, most notably the Primitive Object Volatile Explorer (PrOVE) mission[11] that is the subject of a Planetary Science Deep Space Small Satellite (PSDS3) study, which would have parked at an Earth Lagrange point and targeted a passing new comet.

At present, all missions to Small Bodies have been launched with a specific target in mind, requiring specific launch windows. In fact, it is hard to envision a scenario in which that is not the most effective approach for a spacecraft near Earth. However, in a future in which the starting point might be anywhere in the Solar System (for example, at the conclusion of an exploration of one body, when the spacecraft is ready to be used somewhere else), autonomy in mission design would be enabling.

Assumption(s): the following supporting capabilities are assumed:

- **Computing capability** for establishing necessary situational awareness of the environment and reasoning about situation and self.
- **Miniaturized instruments** such as imagers, spectrometers, radar, or whatever else this pathfinder mission would need.
- **Capable propulsion:** propulsion with enough ΔV to enable access to a reasonable number of Small Bodies. For a pathfinder study such as this, the knowledge gained from studying any Small Body would represent enough of an advance that target choice could be based on trajectory considerations alone, but a detailed study would need to be done to determine what ΔV is required to provide the desired number of launch opportunities. A database of round-trip missions[12] documents several NEOs for which the total required ΔV is less than 5 km/s, and for a one-way trip, there are NEOs accessible with ΔV less than 1 km/sec.

DRM 2: Mother/Daughter Craft to understand the Small Body Population

Synopsis: The mission 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 Small Bodies. The mother craft will dispatch daughter craft to explore diverse bodies (including opportunistic visits to interstellar objects or hazardous objects). These daughter craft will visit the targets to collect samples and return material to the mother craft for further analysis or for resource extraction.

Benefits: The ultimate goal is cursory exploration of the entire population of Small Bodies, or at least a large enough sample to have confidence that it is representative. If this goal is

---

[11] Primitive Object Volatile Explorer, https://www.hou.usra.edu/meetings/smallsat2018/pdf/14_Hewagama.pdf

[12] https://cneos.jpl.nasa.gov/nhats/intro.html

approached one mission at a time, through carefully pre-planned explorations, there will be progress, but not at the pace that could be achieved with highly autonomous systems. The benefit here is to *affordably explore a large number of diverse* Small Bodies with minimal human intervention and minimal communication with Earth. Given the diversity of Small Bodies, which ones are first to be explored is not important, although characterization of the body to be explored becomes more important as the number explored grows. This DRM would result in a more comprehensive understanding of Small Bodies for science, ISRU, and planetary protection—including knowledge that will eventually enable diverting Small Bodies, if necessary. To truly explore the diversity of Small Bodies, it is most efficient to have each spacecraft involved explore as many bodies as possible. If there is no need for samples, the spacecraft could utilize resources identified along the way. However, if samples are to be returned anyway, it provides an opportunity to refuel for spacecraft that are not going to volatile-rich bodies, allowing more flexibility in the design of the system.

Related Work: The science objectives of this DRM are similar to the near-term DRM described above, but increased autonomy further expands the capabilities of the mission (e.g., by increasing the diversity of Small Bodies that can be investigated). In some ways, this DRM is a greatly expanded version of missions like the proposed Main-belt Asteroid and NEO Tour with Imaging and Spectroscopy (MANTIS)[13] Discovery mission, intended to study nine NEOs and main-belt asteroids, albeit with a single spacecraft.

Assumption(s): in addition to the assumptions listed for the near-term DRM, this DRM would require:

- **Material extraction tools** (including some deep-sampling tools for resource extraction)
- **Low-power communication among spacecraft** for communication among daughter craft and between daughter craft and mother craft

---

[13] Main-belt Asteroid and NEO Tour with Imaging and Spectroscopy, https://ieeexplore.ieee.org/document/7500757

Autonomy Capabilities needed for DRMs 1 and 2

Table 3: Mapping DRM Capabilities to Functions and Technologies

Functional Group	Function	Technology Area	Critical for DRM 1?	Autonomous Systems Capability Leadership Team Taxonomy	DRM 2: Long-term (2040+)													
							DRM 1: Near-term (2030)											
					Coord multiple assets	Identify target bodies	Design mission	Cruise	Characterize body	Approach	Land safely	Land at target	Move on surface	Analyze subsurf.	Manipulate surface	Refuel / ISRU	Return to mother	Refuel mother
Identify Body pre-Cruise	Identify target body based on intent	Monitoring and **identification** of Small Body **targets based on a priori defined criteria.** **Reasoning and selecting among** multiple candidate **target bodies based** on an a priori identified criteria		**Situation Awareness** 1.1 Sensing and Perception 1.5 Event and Trend Identification **Reasoning and Acting** 2.1 Mission Planning and Scheduling	🟩	🟩	🟩	🟩										
	Estimate body's trajectory	**Target detection** and **tracking** from millions of km distance; defining models for objects' motions		**Situation Awareness** 1.1 Sensing and Perception 1.3 Knowledge and Model Building			🟩	🟩										
	Design mission trajectory	**Sensing, perception and estimation** of small body trajectory from an Earth orbit or an Earth-Sun L1 **Trajectory planning** to reach a Small Body given spacecraft capabilities and onboard resources		**Situation Awareness** 1.1 Sensing and Perception 1.2 State Estimation and Monitoring 1.3 Knowledge and Model Building			🟩	🟩										
Cruise	Cruise to target vicinity	**Execution of** planned spacecraft, orbit determination and trajectory correction maneuvering	Y	**Reasoning and Acting** 2.1 Mission Planning and Scheduling 2.2 Activity and Resource Planning … 2.4 Execution and Control				🟩										
Model	Identify body's rotation parameters	**Feature/landmark detection** and **tracking** that are robust to shape, surface texture, lighting, rotations **Pose and rate estimation** of body rotation (periodicity, center of rotation, axes of rotation and nutation)	Y	**Situation Awareness** 1.2 State Estimation and Monitoring						🟩	🟩	🟩	🟩					

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

Table 3: Mapping DRM Capabilities to Functions and Technologies

					DRM 2: Long-term (2040+)													
							DRM 1: Near-term (2030)											
Functional Group	Function	Technology Area	Critical for DRM 1?	Autonomous Systems Capability Leadership Team Taxonomy	Coord multiple assets	Identify target bodies	Design mission	Cruise	Characterize body	Approach	Land safely	Land at target	Move on surface	Analyze subsurf.	Manipulate surface	Refuel / ISRU	Return to mother	Refuel mother
	Build 3D model of body	**3D shape reconstruction** (e.g., Shape-from-Silhouette (SfS); Structure from Motion (SfM); photoclinometry)	Y	**Situation Awareness** 1.3 Knowledge and Model Building						🟩	🟩	🟩	🟩					
Identify Surface Composition	Identify water content	**Automated calibration**, **parameter setting** and tuning of instruments for remote and in situ measurements with considerations to lighting direction, pointing, and placement (for in situ). **Assessment of quality** of measurements. **Analyses and uncertainty quantification** of spectra to determine presence and abundance of water, elements or minerology within a single spectrum, across multiple spectra, or through an evolving spectrum, (dynamic situation) **Data-driven re-targeting of measurements**: identify signatures of interest and retarget same or other instruments for additional and more resolved measurements (e.g., multi-spectral micro-imager on a positioning device). **Modeling measurement process** to enable reasoning about the acquisition and measurement data	Y	**Situation Awareness** 1.1 Sensing and Perception 1.2 State Estimation and Monitoring 1.5 Event and Trend Identification **Engineering and Integrity** 4.4 Modeling and Simulation					🟩					🟩		🟩		
	Identify elemental composition								🟩					🟩				
	Identify mineralogy								🟩					🟩				
Identify Interior	Characterize internal heterogeneity and assess large-scale porosity	**Characterize** internal **heterogeneity** via radar, thermal imaging, gravity-field mapping, and seismometry for both science and ISRU. **Assess hazard** due to porosity that can cause major disruption of the body. Needed for deep sub-surface access.		**Situation Awareness** 1.1 Sensing and Perception 1.2 State Estimation and Monitoring 1.3 Knowledge and Model Building					🟩				🟩	🟩	🟩			

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

Table 3: Mapping DRM Capabilities to Functions and Technologies

Functional Group	Function	Technology Area	Critical for DRM 1?	Autonomous Systems Capability Leadership Team Taxonomy	DRM 2: Long-term (2040+)													
							DRM 1: Near-term (2030)											
					Coord multiple assets	Identify target bodies	Design mission	Cruise	Characterize body	Approach	Land safely	Land at target	Move on surface	Analyze subsurf.	Manipulate surface	Refuel / ISRU	Return to mother	Refuel mother
	Map gravity field	Map gravity field to inform close approach and landing as well as interior composition (for science). May need multiple spacecraft for precise measurements. (difficult to do on bodies that are < 10 km; for > 10 km, this would be critical for approaching and landing).							🟩	🟩	🟩	🟩						
	Map magnetic field	For science purposes only							🟩									
Sense Dynamic Environ.	Assess presence of moons or orbiting debris critical for mission safety during approach	**Sensing and perception and tracking** of potential hazards **Change detection** in the vicinity of or on the body **Assessment of** potential **hazards** on spacecraft	Y	**Situation Awareness** 1.1 Sensing and Perception 1.2 State Estimation and Monitoring 1.3 Knowledge and Model Building 1.4 Hazard Assessment		🟩	🟩	🟩	🟩	🟩	🟩							
	Detect presence of jets of gas, plumes of dusts through vents near or on the body								🟩	🟩	🟩	🟩						
Characterize Body for Landing	Characterize surface albedo and variations	**Characterization of surface albedo:** requires body model, Sun direction **Outlier detection** to identify unique sampling targets in addition to common material targets. **Data fusion:** co-registration from heterogenous sensors at different scales/resolutions (both science, e.g., composition) and engineering instruments (e.g., topography)). Requires global localization in a dynamic environment to identify common material and outliers, both of which are likely targets for sample collection.	Y	**Situation Awareness** 1.1 Sensing and Perception 1.2 State Estimation and Monitoring 1.3 Knowledge and Model Building					🟩									
	Assess surface hazards for landing	Characterization of surface slope relative to gravity, roughness, and boulders at the scale needed for landing from approach imagery (depends on spacecraft design but typically at ~20-30 cm)	Y	**Situation Awareness** 1.4 Hazard Assessment					🟩	🟩	🟩	🟩						
Appro	Precision targeting	**Planning** spacecraft **approach trajectory** based on models of body motion during approach	Y	**Reasoning and Acting** 2.1 Mission Planning and Scheduling 2.4 Execution and Control					🟩									

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

Table 3: Mapping DRM Capabilities to Functions and Technologies

					DRM 2: Long-term (2040+)													
							DRM 1: Near-term (2030)											
Functional Group	**Function**	**Technology Area**	**Critical for DRM 1?**	**Autonomous Systems Capability Leadership Team Taxonomy**	Coord multiple assets	Identify target bodies	Design mission	Cruise	Characterize body	Approach	Land safely	Land at target	Move on surface	Analyze subsurf.	Manipulate surface	Refuel / ISRU	Return to mother	Refuel mother
	Approach and landing	**Selection of landing target** based on landing hazard assessment maps, surface and interior composition, and other relevant criteria Guidance and control for 6-Degree of Freedom spacecraft during final approach and landing	Y	**Reasoning and Acting** 2.2 Activity and Resource Planning and Scheduling 2.4 Execution and Control						🟩	🟩							
Characterize Body for Mobility	Model surface topography	**Construction of 3D surface topography** at a scale to enable surface mobility; co-registration of data from multiple vantage points on surface or near surface*: slope relative to gravity, roughness, and boulders	Y	**Situation Awareness** 1.1 Sensing and Perception 1.2 State Estimation and Monitoring 1.3 Knowledge and Model Building **Collaboration and Interaction** 3.1 Joint Knowledge and Understanding 3.2 Behavior and Intent Identification					🟩		🟩	🟩	🟩	🟩				
	Characterize surface physical properties	**Characterization of grain-size distribution** (for science, mobility and manipulation), cohesion of surface particles (for operations including manipulation of material, sample handling). Informs surface interaction	Y						🟩		🟩	🟩	🟩	🟩				
	Assess surface regolith porosity	**Characterization surface porosity** through contact and surface compression at the scale that will impact mobility and manipulation							🟩				🟩	🟩				
	Observe interaction with surface from standoff distance	**Perception** and **modeling of interaction** between an asset and the surface as observed by another spacecraft from a stand-off distance (e.g., observe DART impact, mother craft observing daughter craft like Rosetta observing Philae).			🟩										🟩			
Mobility and Manipulation	Surface Mobility	**Assessment of mobility hazards** (see handling dynamic environment) **Identification of targets** based on surface/subsurface characterization **Surface motion planning** to reach designated target while avoiding hazards **Executing mobility actions** to reach specific destinations within specific timeframes (dense vs. sparse coverage, targeting vs. exploration) **Pose estimation** (relative and absolute position and attitude) of spacecraft. Critical for both engineering and science measurement	Y	**Situation Awareness** 1.4 Hazard Assessment 1.5 Event and Trend Identification **Reasoning and Acting** 2.2 Activity and Resource Planning and Scheduling 2.3 Motion Planning 2.4 Execution and Control									🟩					
	Small-scale surface manipulation	Target selection for sampling; sampling and sample handling Sample **measurements** and **analysis** (see identify surface composition)	Y	**Situation Awareness** 1.4 Hazard Assessment										🟩				

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

Table 3: Mapping DRM Capabilities to Functions and Technologies

Functional Group	Function	Technology Area	Critical for DRM 1?	Autonomous Systems Capability Leadership Team Taxonomy	DRM 2: Long-term (2040+)													
							DRM 1: Near-term (2030)											
					Coord multiple assets	Identify target bodies	Design mission	Cruise	Characterize body	Approach	Land safely	Land at target	Move on surface	Analyze subsurf.	Manipulate surface	Refuel / ISRU	Return to mother	Refuel mother
	Small-scale plume sampling	**Operating and sampling** from a vent of a comet, where interaction with the vent is dynamic in nature or sampling in the vicinity of the vent where different dynamic hazardous conditions exist		1.5 Event and Trend Identification **Reasoning and Acting** 2.2 Activity and Resource Planning and Scheduling 2.3 Motion Planning 2.4 Execution and Control										🟩				
Below-Surface Access	Large-scale surface manipulation (e.g. excavation)	Anchoring or holding on to the surface based on estimation of instantaneous local conditions; manipulation of large surface blocks; decomposition of large blocks into manageable entities **Sorting** through large heterogeneous regolith and rocks Deep **subsurface access** and material extraction **Implanting of instruments** (either temporarily or permanently) for anchoring or for diversion for ones that are a planetary defense hazard.		**Situation Awareness** 1.4 Hazard Assessment 1.5 Event and Trend Identification **Reasoning and Acting** 2.2 Activity and Resource Planning and Scheduling 2.3 Motion Planning 2.4 Execution and Control											🟩			
	Access 1-2 m below surface for ISRU	**Anchoring** or holding on to penetrate to subsurface **Deep subsurface access** and material extraction Transferring and processing large amounts of material													🟩	🟩		
Refueling	Refuel spacecraft using in situ resources	Extraction of material, processing, and handling to refuel surface asset using in situ resources (avoids need for return trips to centralized platform for refueling and enables moving from one target body to another with orbits that are progressively harder, which would otherwise be harder to access from Earth)		**Situation Awareness** 1.1 Sensing and Perception 1.5 Event and Trend Identification 1.2 State Estimation and Monitoring 1.3 Knowledge and Model Building **Reasoning and Acting** 2.1 Mission Planning and Scheduling 2.2 Activity and Resource Planning and Scheduling 2.4 Execution and Control 2.7 Adapting and Learning												🟩	🟩	
	Return to centralized Platform	Return of collected samples to centralized platform for later pick for return to Earth for full characterization in terrestrial laboratories (avoids requiring exploratory spacecraft to re-enter Earth's atmosphere; eliminates the need to have a team to deal with the samples at the time of return)														🟩	🟩	
	Refuel centralized platform	Return to refuel centralized platform using resources collected from volatile-rich bodies.														🟩	🟩	
Spac	Monitor and manage health of spacecraft	Fault prognosis, detection, diagnoses and response. Learning and adapting for past spacecraft experience	Y	1.5 Event and Trend Identification 1.6 Anomaly Detection 2.5 Fault Diagnosis and Prognosis	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

Table 3: Mapping DRM Capabilities to Functions and Technologies

Functional Group	Function	Technology Area	Critical for DRM 1?	Autonomous Systems Capability Leadership Team Taxonomy	DRM 2: Long-term (2040+)													
							DRM 1: Near-term (2030)											
					Coord multiple assets	Identify target bodies	Design mission	Cruise	Characterize body	Approach	Land safely	Land at target	Move on surface	Analyze subsurf.	Manipulate surface	Refuel / ISRU	Return to mother	Refuel mother
	V&V spacecraft	V&V of autonomous capabilities; test and evaluation through modeling, simulation, test beds and multiple mission	Y	2.6 Fault Response 2.7 Adapting and Learning **Engineering and Integrity** 4.1 Validation and verification 4.2 Test and Evaluation 4.4 Modeling and simulation 4.5 Architecture and Design	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Ground Systems	On-demand interaction with autonomous spacecraft using ground stations.	Y		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

---

* Need to think about what drives higher accuracy. Some applications may not require that. Perhaps first mission can get away with lower accuracy. At the scale of the lander (typically 20 cm)

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

Table 4: Assessment of technologies needed for near-term DRM 1

Phase	Technology	State of the Art	Technology Gaps	Supporting Technologies	Relevant Research and Development (R&D) Projects (NASA, industry, academia)	Challenges and Risks	Key Points and Questions
From Earth Orbit (millions of km from Body)	Target identification based on intent	Autonomous detection of vehicles and pedestrians in autonomous transportation	Limited sensed information due to very remote bodies	Advanced computing w/ graphics processing unit (GPU) capabilities Miniaturized high-quality optics High-resolution sensors in visible and infra-red	Autonomous vehicle identification of objects (pedestrians/vehicles) at a distance.	Having highly resolved images at astronomical distances with full coverage Limited sensing and computing onboard SmallSats in Earth's orbit compared to Earth assets	Degree of applicability of industry capabilities. SmallSats in different locations (such as the Earth-Sun L4 or L5 Lagrange points, or at some random location in the Inner Solar System) after studying a particular body, could easily carry technology to be the most effective way to search the surroundings.
	Remote (astronomical distance) target detection with large area coverage	Several surveys devoted to discovery of Small Bodies, mostly searching for Near-Earth Objects, but also for objects as distant as trans-Neptunian objects. Many of these have at least some autonomy in their detection system, but none is fully autonomous at this point.	Fully autonomous target identification from both Earth and in space for remote bodies Identification of objects millions of kilometers using low-mass, low-cost designs		NASA's astrophysics	Onboard capability for detecting and tracking remote objects with weak signals	
	Estimation of trajectory of target body				Ground-based navigation tools (e.g. NASA Jet Propulsion Laboratory [JPL] Mission Analysis, Operations, and Navigation Toolkit Environment [MONTE] [10])	Limited observations with limited sensors and optics at large distances	
	Planetary trajectory planning	Ground-based process with human experts in the loop	Onboard trajectory planning with associated ephemeris information	Ground-based trajectory planning tools Advanced computing	None	Capturing human expertise in trajectory design into codified algorithms. Complex space with numerous options with multiple optimization criteria	
	Cruising to target body vicinity	Ground-based radiometric and optical navigation. Autonomous optical navigation used on Deep Space 1 [2]	End-to-end autonomy that handles constraints, resources and health	Affordable and low-mass propulsion with $\Delta V >> 1$ km/s	Industrial development of propulsion technologies; small R&D and flight efforts but with limited scope	Requires robust reasoning to handle a range of conditions and avoid critical failures	
On Approach	Landmark-based feature tracking	Ground-based manually-intensive terrain-relative navigation using Stereo-Photoclinometry (SPC)	Automated landmark extraction. V&V of feature tracking algorithms	Advanced computing w/ GPU capabilities Miniaturized high-quality optics High-resolution sensors in visible and infra-red	Simultaneous Localization and Mapping (SLAM) techniques from robotics domain Machine learning for robust feature tracking	Robustness to lighting changes, long sharp shadows, low-albedo and occlusions Achieving low-uncertainty in estimation	Currently, these tasks require heavy ground-in-the-loop analysis, often with multiple teams

Table 4: Assessment of technologies needed for near-term DRM 1

Phase	Technology	State of the Art	Technology Gaps	Supporting Technologies	Relevant Research and Development (R&D) Projects (NASA, industry, academia)	Challenges and Risks	Key Points and Questions
	Pose and pose rate estimation	Ground-based data fusion: reconstruction using SPC-based shape models [11]; star trackers for spacecraft attitude changes, Deep Space Network (DSN) range/rate and far-field asteroid imagery for orbit determination.	Autonomous relative navigation between spacecraft and body and using onboard feature tracking V&V testbed	Estimation filtering techniques	NASA orbital ground-based navigation techniques SLAM techniques from robotics domain [12]	Robust landmark targeting and low-uncertainty using efficiency onboard algorithms	Currently, these tasks require heavy ground-in-the-loop analysis, often with multiple teams
On Approach (1,000+ – 1+ km)	Object 3D Modeling	Ground-based manually-intensive model reconstruction using SPC-based [3] and Stereo-based Photogrammetric (SPG) approaches [4].	Onboard autonomous shape reconstruction with ability to handle uncertainties in spacecraft pose, body rotation, and lighting variations	Advanced computing Data representations	3D scanning and model building; Shape-from-silhouette; Extensive real-time point-cloud mapping in terrestrial robotics applications / self-driving cars	Data fusion across large scale changes that is robust to different body rotations, geometries, albedo and lighting conditions	Currently, these tasks require heavy ground-in-the-loop analysis, often with multiple teams
	Rendezvous guidance and control	Flyby and impact missions use narrow angle camera for relative pose estimation. Autonomous correction maneuvers for targeted impact/flyby (e.g., DART's SmartNav system)	Control of low-thrust maneuvers for precision rendezvous. Control of single large arrival burn maneuver.	SmallSat propulsion systems. High-quality NavCam Optics for SmallSats.	Industrial development of propulsion technologies;	Managing uncertainties to avoid collision with body	
Instruments (1	Spectral instrument parameter setting	Manually tuned settings by instrument experts	Autonomous tuning and parameter setting	Signal processing Machine learning Miniaturized low-power instruments that are robust to a wide range of environmental conditions	Ground-based automated tools used in missions	Capturing human experience of operating instruments in relevant environment	

Table 4: Assessment of technologies needed for near-term DRM 1

Phase	Technology	State of the Art	Technology Gaps	Supporting Technologies	Relevant Research and Development (R&D) Projects (NASA, industry, academia)	Challenges and Risks	Key Points and Questions
	Spectral analysis (and uncertainty quantification)	Manually analyzed on the ground to characterize Small Bodies (Hayabusa, Rosetta, Hayabusa2, OSIRIS-REx, and NEAR Shoemaker*)* Interior composition inferred from gravity field	Autonomous characterization of bodies Direct measurement of interior composition	Knowledge databases for interpreting and reasoning about measurements Instrument capable of subsurface measurements	Defense Advanced Research Projects Agency (DARPA) Program: Artificial Intelligence for Chemistry (for data analysis) Currently used ground tools for spectral analysis	Onboard, computationally-efficient, expert-informed analysis databases and tools	Whether the basic characterization done by mission science teams can be adapted to be done autonomously.
	Science-data decision-making	Carefully-orchestrated measurement campaigns for in situ science, often planned weeks in advance. Changes to campaigns occur only after ground-based analysis of the data returned shows that either some measurements do not meet the mission's requirements or some measurement(s) indicates an unanticipated phenomenon.	Onboard interpretation and understanding of measurement analyses to inform subsequent commanding	Neural computing Ability to process and interpret heterogenous information Spectral analysis	Machine learning used for Earth science mission and for terrestrial applications (e.g., agriculture, retail, etc.)	Codification of domain expertise in algorithms that allow for more rapid analyses and interpretation measurements to guide future actions. Stating mission goals in advance in a manner that an autonomous system can evaluate, rather than specific numerical goals for specific measurements.	Ability to assess whether overarching goals are achieved and to rapidly respond rapidly to unexpected occurrences
Descent and Landing (1 km – 0 m)	Multi-modal data fusion	Fusion of inertial, star tracking and sun sensing data to estimate attitude. Radar or lidar to estimate altimetry for touch-and-go maneuvers.	Autonomous fusion of high-density Lidar scans with descent imagery. Real-time shape-model refinement during descent.	Efficient storage and manipulation of large data sets Computing and memory	3D mapping for autonomous vehicles Visual/inertial fusion and 3D mapping from aerial platforms	Computationally efficient algorithms for multi-sensor modality data fusion Mathematical techniques for managing uncertainty Robustness to varying topographies and lighting conditions	Robustness to variations Computation efficiency to act in time (i.e., real-time)
	Surface hazard assessment for landing	Extensive remote monitoring to manually identify any landing hazards.	Autonomous evaluation of rough topography in non-uniform gravity model for safe-landing zones that are within controllability of the spacecraft	Wide-coverage sensors with high resolution to detect hazardous terrains pre-landing Low-mass sensors Computing	NASA's Autonomous Landing Hazard Avoidance Technology (ALHAT) (JSC/JPL) [5]	Fast and small moving objects that require detection at remote distances. Completeness: ability to detect all hazards	Can we detect all hazards autonomously in such extreme environment?

Table 4: Assessment of technologies needed for near-term DRM 1

Phase	Technology	State of the Art	Technology Gaps	Supporting Technologies	Relevant Research and Development (R&D) Projects (NASA, industry, academia)	Challenges and Risks	Key Points and Questions
	Small Body vicinity hazard detecting and tracking for close approach and landing	Ground-based processing analysis of images of landing site. Manual assessment of hazards and identification for safe maneuvers.	Autonomous detection of orbital debris, and outgassed/ejected material. Real-time refinement of surface model and hazard map.	Advanced computing	Image-processing techniques for change detection Autonomous vehicle industry tracking of multiple objects surrounding a vehicle	Extraction of accurate-enough motion models. Building dynamic trajectory models from limited observations	Ability to detect and predict dynamic hazards
	Spacecraft guidance and control near body	Ground-based radiometric and optical navigation based on landmarks. Well-orchestrated maneuvers for getting close to the surface (e.g., landing or touch-and-go). Only final 10s of meters executed autonomously	Fully autonomous descent, landing, touch-and-go, and return to "home" position. Ability to redirect or abort in response to detected hazards and anomalies.	Advanced computing Algorithms to estimate body motion Controlled maneuvering (precise and efficient thrusters)	NASA/JPL internal Research and Technology Development Program funding in proximity operations	Non-convex optimization for guidance Algorithm and computational complexity Controllability of the spacecraft (maneuvering)	Ability to react to dynamic hazards in real-time
	Multi-objective landing-site selection (value and safety)	Landing site selection requires months of mapping and deliberation from ground control.	Autonomous generation of risk/value surface maps. Algorithms for selecting safe and valuable landing sites to meeting mission objectives	Hazard assessment for landing	NASA's ALHAT program	Ability to assess value of sites remotely. Ability to weigh multiple, potentially competing objectives Derive metrics for landing site "value" based on high-level science goals.	
Surface Operations (0 m)	Target selection/ refinement from surface	Ground-based expert-driven surface target selection to be reached by surface assets	Target value assessment	Multi-sensor data fusion and autonomous spectral data analysis	Machine learning for spectral images (JPL/Ames Research Center)	Co-registration of composition data acquired during approach with data acquired on the surface	Forgiving: consequence of a false positive or false negative is not grave
	Multi-vantage point mapping	Ground-based mapping with some manual intervention for co-registration of orbital and surface asset-based imagery	Onboard mapping of data at various scale and from various vantage points	Advanced computing and large storage	Autonomous vehicles mapping	Mapping from low-vantage point of being on the surface of the body Managing heterogeneous uncertainty in the data	
	Change detection	Detection of dynamic events such as plumes [6] and Mars' dust devils [7]		Image processing and machine learning for visual detection	Visual inspection in medical field	Identifying subtle changes Signal to noise ratios	Mature technology exists

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

Table 4: Assessment of technologies needed for near-term DRM 1

Phase	Technology	State of the Art	Technology Gaps	Supporting Technologies	Relevant Research and Development (R&D) Projects (NASA, industry, academia)	Challenges and Risks	Key Points and Questions
	Estimation of surface physical properties	Image-based terrain classification on Mars rovers. Wheel-slip estimation and adaptive control on Mars rovers (MSL). Ground-based post-impact estimation of coarse surface parameters by humans (e.g., coefficient of restitution from Philae lander bounce). Ground-based inference of surface properties from geological features (e.g., rocks and craters)	Onboard modeling of regolith dynamics and granular media in microgravity. Estimation of surface properties from remote observations. Estimation of surface terra-mechanical properties from brief, dynamic contact. Measurement and estimation of surface electrostatics.	Terra-mechanical models Particle-based terra-mechanical simulations. Experimental test beds for regolith contact dynamics in reduced gravity.	Academic research in terra-mechanics Army research in mobility impacted by terra-mechanics. Limited characterization of detailed surface properties from prior missions. NASA project for terrain classification based on thermal inertia.	Models are largely empirical Models limited to homogeneous terrains. Interactions with the surface in microgravity are typically brief/transient.	Complex dynamics but lower fidelity may be required for mobility
	Target selection/ refinement from surface	Surface hazards for touch-and-go maneuvers only assessed from distant imagery. Hazard assessment for Mars rovers, but in more benign terrains	Traversability and hazard models for surface mobility. Visual hazard detection from near-surface vantage point	Miniaturized high-quality visual inertial sensors. Advanced onboard computing.	NASA's Small Body autonomous surface navigation [8]	Hazard assessment is a function of the capability of the surface asset. Extreme terrain topography and platform design redefine what hazards would be	Can all hazards be detected autonomously to avoid premature mission ending?
Surface Operations (0 m)	Surface pose estimation and localization	Mars rovers visual inertial estimation. Secondary landers (Philae, MIcro-Nano Experimental Robot Vehicle for Asteroid [MINERVA], Mobile Asteroid Surface Scout [MASCOT]) have all relied on mother spacecraft for localization.	Surface attitude determination and self-righting. Vision-based localization during ballistic hops and on surface. Real-time map refinement Localization/navigation in shadowed regions.	Miniaturized high-quality visual inertial sensors (e.g., cameras and Lidars) Dust-shedding technologies Advanced onboard computing.	SLAM techniques from robotics domain (surface vehicles and drones) Terrain-relative navigation and guidance for small body touch-and-go maneuvers.	Visually challenging environment with rapidly changing illumination and scale during hops Dust/plume lens contamination. Lander may settle in surface concavities that occlude far-field visibility and communication. Mobility asset rotation/tumbling on surface that may result from low-gravity environments.	

Table 4: Assessment of technologies needed for near-term DRM 1

Phase	Technology	State of the Art	Technology Gaps	Supporting Technologies	Relevant Research and Development (R&D) Projects (NASA, industry, academia)	Challenges and Risks	Key Points and Questions
	Surface motion planning	Mars rovers motion planning. Highly orchestrated and constrained (one-dimensional ascent/descent) touch-and-go maneuver trajectories.	Complex motion trajectories for heterogenous surface assets (e.g., hopping/ tumbling). Reasoning and risk and value and decision-making. Planning information-gathering actions to reduce uncertainty (e.g., hop up to map local area or “poke” surface to probe mechanical properties). Adaptive methods for planning with model refinement.	Advanced onboard computing. Ruggedized microgravity surface mobility platforms. Sensing and state estimation on surfaces of Small Bodies.	Mars Technology Program (2001-2007). NASA Innovative Advanced Concepts (NIAC) projects on Small Body autonomous surface navigation [9]	Extreme-terrain topography with non-traditional surface mobility platforms. Navigating in a complex and uncertain gravity environment. Possibility of “escaping” the body or getting “stuck” in a crack or deep regolith.	Complex and dynamic interaction between surface assets require in situ information to make informed and timely decisions
	Surface Mobility and control	Conventional TAG maneuvers are highly staged and quickly return to “home” orbit. Short, random hopping demonstrated with small secondary landers via internal actuation (MINERVA and MASCOT)	Targeted mobility to multiple destinations. Control of hopping, tumbling, and impacting on small bodies. Dust mitigation strategies.	Terramechanics models and simulations of regolith in microgravity. Experimental test beds for regolith contact dynamics in reduced gravity. Surface localization and pose estimation.	Spacecraft/Rover Hybrids (Hedgehog) NIAC project. JPL’s “Limbed Excursion Mechanical Utility Robots (LEMUR)” climbing robot Applied Physics Laboratory’s (APL) NASA-funded “POGO” project for Asteroid Redirect Mission (ARM) mission.	Highly irregular and granular surfaces with unknown shapes and physical properties. Dynamics in microgravity make it difficult to control surface contact forces.	
	Surface sampling and handling	Short-duration sampling during TAG with mechanisms such as brush drums and gas jets	Coring to preserve stratigraphy. Measuring sample quantity	Autonomous scooping, drilling, or other sampling technologies	Mars, Venus and other planetary mission sampling techniques. Bi-blade sampler at JPL	Very low pre-loading for sampling hard material	
Below Surface	Anchoring	Philae attempted anchoring with drills and harpoons, but both failed.	Ballistic anchoring (e.g., harpoons) or gentle anchoring (e.g., drills, hammer penetrators) strategies Resisting contact forces to remain grounded.	Grasping, grappling, straddling	ARM-mission techniques for grasping: gripping using micro-spines.	A priori unknown and highly variable terrain properties. Small forces can induce ballistic motion away from surface	

NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

Table 4: Assessment of technologies needed for near-term DRM 1

Phase	Technology	State of the Art	Technology Gaps	Supporting Technologies	Relevant Research and Development (R&D) Projects (NASA, industry, academia)	Challenges and Risks	Key Points and Questions
	Large-object manipulation	ARM-mission studies and terrestrial prototypes. No flown missions.	Grasping/grappling techniques for large boulders. Spacecraft control with heavy distal payload	Lightweight, high-strength space robotic manipulators	Mining-industry autonomous extraction (horizontal mining). ARM-mission techniques for grasping: micro-spine gripper.	Uncertainty associated with interacting with terrain (including friability and material strength). Small forces can induce ballistic motion away from surface	
	Deep surface access (> 2 m)	Terrestrial drilling for oil and gas. No relevant missions or demonstrations	Drilling in microgravity regolith and rock.	Deep drilling Burrowing Insight's HP3 instrument	Honeybee drilling		
	ISRU	No relevant missions or demonstrations	Devices and strategies for excavating large volumes of material. Targeting surface regions with dense resource concentration	Terramechanics models and simulations for regolith in microgravity.	NASA ISRU (JSC)	Energy management. Resources sparsely distributed.	
	Architecture for Autonomous Systems	Custom architecture for each mission; sequence-driven missions	Goal-based, system-level autonomy for end-to-end missions	Software architectures Programming languages	Several products appear on market, but have had limited adoption. In robotics, the Robotics Operating System (ROS) for Open Source Foundation	Heterogeneous space platforms (cruise craft, surface assets, sub-surface assets). Limited market for deep-space applications	

Table 4: Assessment of technologies needed for near-term DRM 1

Phase	Technology	State of the Art	Technology Gaps	Supporting Technologies	Relevant Research and Development (R&D) Projects (NASA, industry, academia)	Challenges and Risks	Key Points and Questions
All Phases	Monitoring and management of spacecraft health	Fault protection on spacecraft (disabled during critical events). Model and data driven techniques (Beacon-based Exception Analysis for Multimissions [BEAM]/ Spacecraft Health Inference Engine [SHINE] [13], Model-based off-nominal state isolation and detection (MONSID) [14])	Fault detection, isolation and recovery for increasingly complex systems	Fault detection, isolation, and recovery (FDIR) technologies Big-data trend identifications Instrumentation of devices and component technologies	Industrial efforts in trend identification for knowledge management companies (Amazon, Google, Facebook) Migration of industries to IoT (e.g., General Electric's instrumentation of flight engines) Aeronautics (NASA, U.S. Air Force, commercial) have technology that could be ported.	Fault identification and isolation Completeness and robustness of diagnosis Prognosis	
	Management and coordination of multiple assets on ground or in space at centralized platform to survey, monitor, characterize and identify targets	Dual spacecraft coordination – Gravity Recovery and Climate Experiment (GRACE) and Gravity Recovery and Interior Laboratory (GRAIL) missions, Mars surface assets and orbits	Multi-asset information sharing, model building, reasoning and decision making. Task negotiation/assignment of functions to spacecraft with distinct specific limited capabilities for a particular scientific or exploration problem.	Communication-based techniques for multi-asset localization	Multi-asset and multi-platform research. Mother daughter co-registration. Orbital surface localization for Mars rovers	Co-registration of approach composition data with surface acquired data Task assignment/negotiation among assets to achieve a function based on capability	
	V&V	V&V limited to well-defined and limited autonomous functions that operate within specific constraints	Techniques that would generalize and scale to more complex systems and scenarios	Mathematical tools for V&V	Testing-based programs for autonomous vehicles. Limited efforts under R&D program at NASA.	Generalization of the approaches and their scalability	Field in infancy and requires substantial development

In summary, the aforementioned technologies would need to be developed, adapted, matured, and tested to achieve DRM 1. There is a further level of specificity for each of these technologies that would be detailed as the mission concept is further fleshed out. Some capabilities such as perception-rich situational awareness and operating on the surface of an unknown environment would generalize to other DRMs, but a well-defined application would be needed to drive the development and evaluation of progress for advancing and achieving autonomy and assessing broader impact.

Part IV: FIndings

The Small Bodies DRM team finds the following actions and activities would enable the DRM scenarios described above.

Consider include engaging industry more effectively:

- Define crisp engineering challenges to present to industry to attract partnerships
- Scour DoD activities that have government rights and offer them to the proposing science community
- Assess applicability of automotive computing, sensing, and reliability standards and capabilities for human-rated AVs to potentially facilitate interoperability of relevant components: sensing, computation, software, etc.

Investments in autonomy for Small Body missions will provide far-reaching benefits. Implementing autonomy for Small Bodies will provide a “playground” for researching, developing, testing, and maturing technologies that can be used in more complex and more expensive mission scenarios. Small Bodies are accessible, diverse, and plentiful. Small Body research embodies challenges that are common to several other DRMs:

- Unknown topography for body mapping
- Extremely rugged surfaces (Europa, Enceladus)
- Dynamic interaction between assets and the environment (Venus, Titan, liquid bodies, etc.)
- A priori unknown surface properties

In addition, Small Body missions have certain advantages that would enable technology development:

- Lower cost for approach and landing
- More forgiving (impact with surface less harmful)
- Accessible via small spacecraft (SmallSats)
- Offer mission of opportunity (flybys of interstellar visitors)

Part V: Team and Contributors

The Small Bodies Design Reference Mission team is comprised of:

- **Shyam Bhaskaran**, Supervisor, Navigation and Mission Design Engineer, NASA JPL
- **Julie Castillo**, Planetary Scientist, NASA JPL/Caltech
- **David Gump**, Former Chief Executive Officer, Deep Space Industries
- **Lute Maleki**, Distinguished Senior Engineer, Sensors/Instruments, Cruise Automation
- **Jay McMahon**, Assistant Professor, Astrodynamics, University of Colorado-Boulder
- **Carolyn Mercer**, Program Executive, Planetary Science Division, NASA HQ
- **Issa Nesnas**, *DRM co-lead*, Principal Technologist in Robotics, NASA JPL
- **Harry Partridge**, Chief Technologist, NASA ARC
- **Marco Pavone**, Assistant Professor of Aeronautics and Astronautics, Stanford
- **Andrew Rivkin**, Planetary Astronomer, Johns Hopkins University APL
- **Timothy Swindle**, *DRM co-lead*, Director of Lunar and Planetary Laboratory, Univ. of Arizona
- **Bob Touchton**, Chief Autonomy Scientist, Advanced Solutions Group, Leidos
- **Gur Kimchi**, Vice President, Prime Air, Amazon

Other Contributors

- **Florence Tan**, Deputy Chief Technologist, Science Mission Directorate, NASA HQ
- **John Jones-Bateman,** Booz Allan Hamilton, Science Communications, NASA HQ
- **Benjamin Hockman**, Robotics Technologist, NASA JPL
- **Felix Gervits**, Student Research Assistant, Tufts University

Part VI: References

[1] https://ieeexplore.ieee.org/document/7500757

[2] Bernard, D., Doyle, R., Riedel, E., Rouquette, N., Wyatt, J., Lowry, M., & Nayak, P. (1999). Autonomy and software technology on NASA's Deep Space One. *IEEE Intelligent Systems and their Applications*, *14*(3), 10-15.

[3] Jorda, L., Gaskell, R., Capanna, C., Hviid, S., Lamy, P., Ďurech, J., ... & Keihm, S. J. (2016). The global shape, density and rotation of Comet 67P/Churyumov-Gerasimenko from preperihelion Rosetta/OSIRIS observations. *Icarus*, *277*, 257-278.

[4] Preusker, F., Scholten, F., Matz, K. D., Roatsch, T., Hviid, S. F., Mottola, S., ... & Vincent, J. B. (2017). The global meter-level shape model of comet 67P/Churyumov-Gerasimenko. *Astronomy & Astrophysics*, *607*, L1.

[5] Epp, C. D., & Smith, T. B. (2007, March). Autonomous precision landing and hazard detection and avoidance technology (ALHAT). In *2007 IEEE Aerospace Conference* (pp. 1-7). IEEE.
[6] Thompson, D. R., Bunte, M., Castano, R., Chien, S., & Greeley, R. (2012). Image processing onboard spacecraft for autonomous plume detection. *Planetary and Space Science*, *62*(1), 153-159.
[7] Castano, A., Fukunaga, A., Biesiadecki, J., Neakrase, L., Whelley, P., Greeley, R., ... & Chien, S. (2008). Automatic detection of dust devils and clouds on Mars. *Machine Vision and Applications*, *19*(5-6), 467-482.
[8] Bhaskaran, S., Nandi, S., Broschart, S., Wallace, M., Cangahuala, L. A., & Olson, C. (2011). Small body landings using autonomous onboard optical navigation. *The Journal of the Astronautical Sciences*, *58*(3), 409-427.
[9] Hockman, B., & Pavone, M. (2017). Stochastic motion planning for hopping rovers on small solar system bodies. In *Proceedings of ISRR*.
[10] Mission Analysis, Operations, and Navigation Toolkit Environment. https://montepy.jpl.nasa.gov/
[11] Gaskell, R.W., "Characterizing and navigating small bodies with imaging data," *Journal of Meteoritics and Planetary Science,* June 2008, vol. 43 Issue: 6, pp. 1049-1061
[12] Reid, I.D., Davison, A.J., Stasse, O., Molton, N.D., "MonoSLAM: Real-Time Single Camera SLAM," in Transaction of Pattern Analysis and Machine Intelligence, June 2007, pp. 1052-1067, vol. 29
[13] James, M.L., Zima, H.P., "An introspection framework for fault tolerance in support of autonomous space systems", IEEE Aerospace Conference, 2008
[14] Kolcio, K, Fesq, L., "Model-based off-nominal state isolation and detection system for autonomous fault management," 2016 IEEE Aerospace Conference, 2016

Small Bodies Design Reference Mission Report Summary

Small Bodies, such as near-Earth objects (NEOs), comets, and asteroids, are abundant and have diverse compositions and origins. Exploring them is important to increase our knowledge in four focus areas: decadal science, human exploration, in situ resource utilization, and planetary defense.

Small Bodies are well-suited targets for advancing autonomy because they embody many of the challenges that are representative of even more extreme destinations, but they are accessible by small affordable spacecraft. 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. 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. Many previous Small Body missions have used some level of autonomy, but all operated within narrow windows and constraints. The missions proposed by the Small Bodies DRM team require autonomy to overcome these challenges and achieve effective mission operations.

The Small Bodies DRM team suggests two autonomous DRM scenarios.

DRM Scenario: A Mission from Earth's Orbit to the Surface of a Small Body

This scenario is a near-term mission (launch in 2030s) that places an affordable small satellite in Earth orbit with a high-level goal of reaching a selected asteroid, approaching and landing on the body, precisely accessing at least one target on the surface, sampling, analyzing the measurements, retargeting follow-on measurements based on local analyses, and sending the results back to Earth—all of which are accomplished autonomously.

This DRM scenario requires a level of autonomy that is not currently available. Advancements in autonomy technology are required for this mission scenario to perform the following:

End-to-end, Long-Duration Autonomy: Operating for a long duration in spite of unknowns, degradations, faults, and failures is crucial. So far, autonomous capabilities have only been used for relatively short mission durations with pre- and often post-monitoring from the ground. This mission 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, autonomy is needed to observe, track, and model the body's trajectory, rotation, and shape at distances from thousands of kilometers (when uncertainties are large) down to the surface to avoid collision. During this operation, autonomy is also required to refine knowledge of the spacecraft's motion and command its maneuvers. Autonomy will allow use of onboard models to assess the hazards in the environment at the scale of the spacecraft 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: Autonomy is needed 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 autonomously monitor and react to such conditions in real time with limited a priori knowledge of the environment.

Proximity Interaction: Autonomy is necessary 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. The mission needs to adapt and learn from its operations autonomously.

Reaching Specific Surface Targets: Autonomy is required 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 is needed to 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.

To enable autonomy in this DRM scenario, advancements in the following supporting technology areas are required:

- Small satellite propulsion with delta V > 1,000 m/s
- Advanced onboard computing and storage
- Advanced sensing and optics
- Surface mobility and mechanisms for subsurface access
- Low mass, low-power, direct-to-Earth communication from small spacecraft

DRM Scenario: Mother/Daughter Craft to Understand the Small-Body Population

This long-term DRM scenario (launch in 2040+) scenario places a centralized mother platform with multiple daughter satellites in Earth orbit to scan, identify, characterize, and eventually enable access to a range of Small Bodies. The mother craft will dispatch daughter craft to explore diverse bodies (including opportunistic visits to interstellar or hazardous objects). These daughter craft will visit the targets to collect samples and return material to the mother craft for further analysis or for resource extraction.

This DRM scenario requires a level of autonomy that is not currently available. In addition to the autonomy technology advancements required by the mission scenario described above (Mission from Earth's Orbit to the Surface of a Small Body), further advancements in autonomy technology are required for this Mother/Daughter Craft mission scenario to perform the following:

Extracting Resources: Autonomy is required to enable anchoring or holding on to the surface and reaching deep into the body—activities which depend on instantaneous local conditions. Autonomy is also needed to support extraction and handling of large volumes of material for processing.

Detecting Small Bodies and Coordinating Multiple Spacecraft: Autonomy is needed to identify Small Bodies in space based on intent, then track and estimate their trajectories. Autonomy is also needed to plan cruise trajectories to the body, coordinate between the mother and daughter spacecraft, and dispatch appropriate daughter spacecraft to specific bodies. For long-term operations, autonomy is required to enable daughter spacecraft to return to the mother, dock and refuel.

Planetary Defense: Planetary defense requires (1) understanding the composition and geotechnical properties of Small Bodies and (2) threat mitigation that demands dealing with a largely unknown interior and surface. Both the understanding and mitigation are best 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.

To enable autonomy in this DRM scenario, advancements in the following supporting technology areas are required:

- Low-mass replenishable propulsion with initial delta V > 5,000 m/s
- Docking/undocking with ability to transfer volatiles
- Advanced onboard computing and storage for long-term operations
- Advanced sensing and optics for remote detection
- Large-scale surface mobility, subsurface excavation, and material handling
- Communication among multiple assets in space, on the surface, and below the surface

Investments in autonomy for Small-Body missions will provide the Agency with far-reaching benefits. Implementing autonomy to enable Small Body missions will provide a “sandbox” for researching, developing, testing, and maturing technologies that can be used in more complex, less forgiving, and more expensive mission scenarios. Small Bodies are accessible, diverse, and plentiful. Small Body research embodies challenges that are common to several other DRMs:

- Unknown topography for mapping and characterizing
- A priori unknown surface properties
- Extremely rugged surfaces (Europa, Enceladus)
- Interaction between assets and the environment (Venus, Titan, liquid bodies, etc.)
- Dynamically hazardous environments (Europa, Enceladus’s plumes)
- Obstructions to line-of-sight communications (Titan, Enceladus’s vents, Europa’s crevasses)

In addition, Small Body missions have certain advantages that would enable technology development:

- Lower cost for approach and landing
- More forgiving (impact with surface is less harmful, slower motions)
- Accessible via small spacecraft

- Offer missions of opportunity (flybys of interstellar visitors)

Findings

The Small Bodies DRM team finds that the following actions and activities would facilitate implementation of the DRM scenarios described above:

1. Establish a one-year project with participation from NASA/industry/academia to flesh out the design details; assess the applicability of external technologies (automotive and logistics industries/government agencies) and identify detailed gaps; provide specification for supporting technologies, including rapid systems engineering; and estimate the cost of developing and verifying/validating the various capabilities
2. Define crisp engineering challenges to seed solicitations for:
    a. Developing a high-fidelity, end-to-end, physics-based simulation to support the development of a fully-autonomous mission to a Small Body using small spacecraft
    b. Developing and maturing the key autonomy technologies using the full lifecycle simulation
3. Establish a project to integrate hardware and software capabilities, test them in simulation, and mature them for flight demonstration
4. Demonstrate capabilities of increased sophistication via a couple of small spacecraft missions and/or extended missions of opportunity