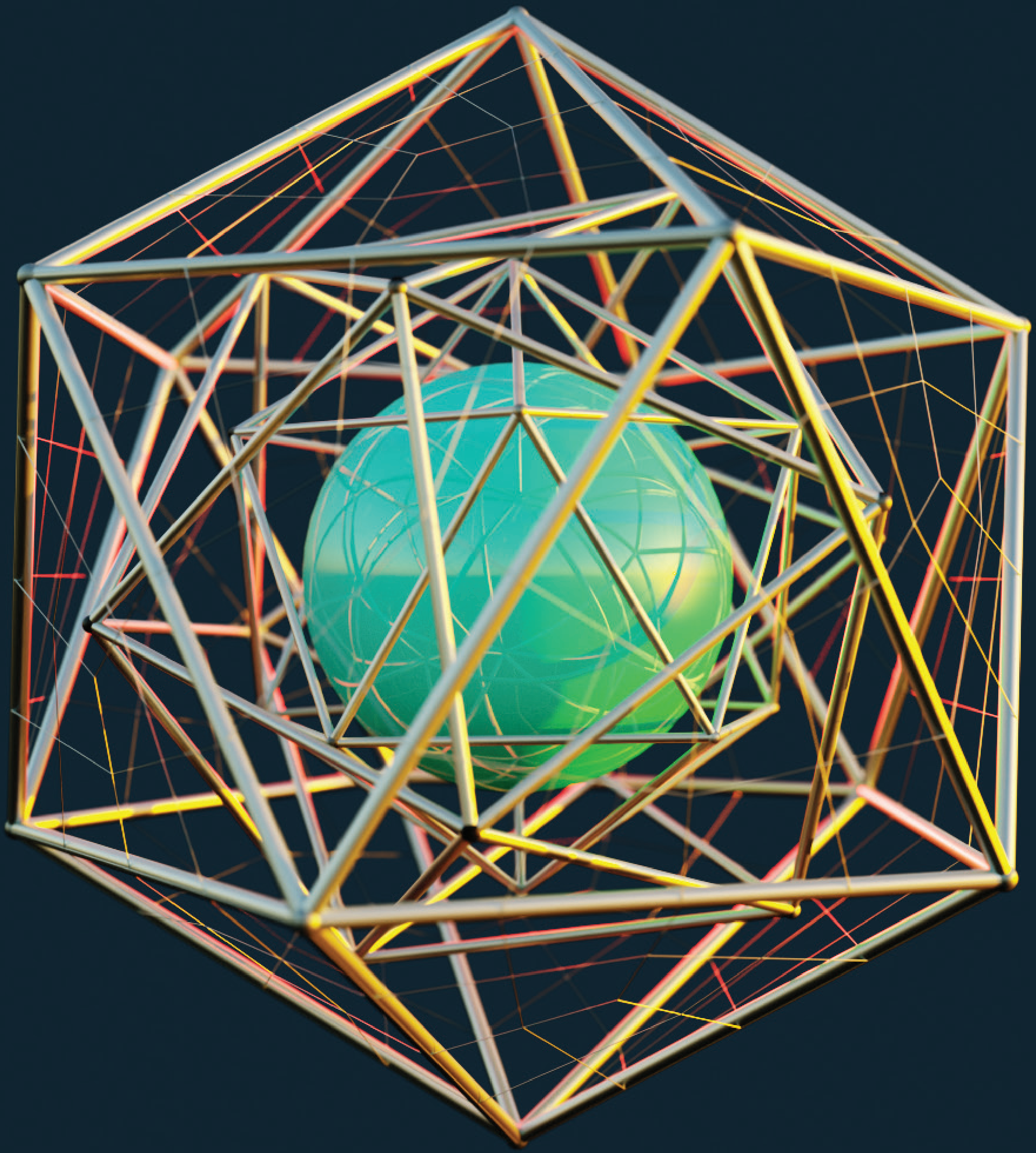

Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions

Part II.
Onboard Guidance, Navigation, and Control (GN&C)

February 28, 2023

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions

Part II. Onboard Guidance, Navigation, and Control (GN&C)

Engineering and Science Directorate
Jet Propulsion Laboratory
for
Planetary Science Division
Science Mission Directorate
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Foreword

Future planetary explorations envisioned by the National Research Council’s (NRC’s) *Origins, Worlds and Life (OWL) 2023–2032*,[1] developed at the request of NASA Science Mission Directorate (SMD) Planetary Science Division (PSD), seek to reach targets of broad scientific interest across the solar system. This goal can be achieved by missions with next-generation capabilities such as innovative interplanetary trajectory solutions, highly accurate landings, the ability to be in close proximity to targets of interest, advanced pointing precision, multiple spacecraft in collaboration, multi-target tours, and advanced robotic surface exploration. Advancements in guidance, navigation, and control (GN&C) and mission design—ranging from software and algorithm development to new sensors—will be necessary to enable these future missions.

Spacecraft GN&C technologies have been evolving since the launch of the first rocket. *Guidance* is the process of generating guidance commands which specify the desired flight path of the vehicle from its current location to a designated target. *Navigation* is the science behind transporting a vehicle from place to place; particularly, the method of determining position, course, and distance traveled. *Control* is defined as the onboard manipulation of vehicle steering controls to track guidance commands while maintaining vehicle pointing with the required precision. As missions become more complex, technological advancements of GN&C systems must keep pace, and the last decade has shown a lot of progress.

This document—Part II, *Onboard Guidance, Navigation, and Control*—is the second in a series of four technology assessment reports evaluating the capabilities and technologies needed for future missions pursuing SMD PSD’s scientific goals. It covers attitude estimation and control in general, as well as the estimation and control of vehicle flight paths when flight path and attitude dynamics are strongly coupled (as is the case during certain critical phases, such as “, and landing, in some planetary missions). These reports cover the status of technologies and provide findings and recommendations to NASA PSD for future needs in GN&C and mission design technologies. Part I, *Onboard and Ground Navigation and Mission Design,* covers planetary mission design in general, as well as the estimation and control of vehicle flight paths when flight path and attitude dynamics may be treated as decoupled or only loosely coupled (as is the case the majority of the time in a typical planetary mission).[2] Part III, *Surface and Sub-Surface Guidance, Navigation, and Contro*l, examines GN&C for vehicles that are not in free flight, but that operate on and below the surface of a natural body of the solar system.[3] For the first time, Part IV, *Aerial Guidance, Navigation, and Control*, examines GN&C for heavier-than-air and lighter-than-air vehicles in buoyant or sustained free flight in the atmospheric environment of a natural body of the solar system.[4] Together, these documents provide the PSD with a roadmap for achieving science missions in the next decade.

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These and other relevant reports can be found at https://solarsystem.nasa.gov/technology-reports/technology-assessment-reports/.

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1 Executive Summary

This document “Onboard Guidance, Navigation, and Control,” is the second in a four-part series assessing the guidance, navigation, and control (GN&C) capabilities and technologies needed for future mission concepts and has been developed at the request of the Science Mission Directorate (SMD) Planetary Science Division (PSD). The development here has been aligned to support future planetary explorations as envisioned in the National Research Council’s (NRC’s) *Origins, Worlds and Life 2023–2032*.[1]

Onboard GN&C is a key spacecraft subsystem that guides and controls the spacecraft in order to achieve a broad range of mission objectives. Such objectives include spacecraft maneuvering, payload and instrument pointing, interplanetary cruise, orbit insertion, orbit maintenance, EDL and landing, and small body proximity operations, among many others. GN&C functions largely occur on board the spacecraft, but there are many design simulations, support, and test functionalities that occur only as part of research and ground operations. GN&C functions divide coarsely into 1) algorithms and software, 2) flight instruments, 3) non-sensing flight hardware, and 4) ground test facilities.

GN&C algorithms and software can be divided into inertial onboard guidance and control and target-relative estimation. Inertial onboard GN&C includes such functions as position and attitude estimation and path control, spacecraft path planning, autonomy systems, and low-thrust guidance. Target-relative GN&C includes such functions as landmark-relative position estimation, and hazard detection and avoidance. *GN&C flight instruments* can be divided into inertial and target-relative sensors. Inertial sensors include star-trackers, gyros, and accelerometers, as well as precision time determination. Target-relative sensing includes altimetry and velocimetry, terrain sensors, hazard-detection sensors, and inter-spacecraft sensors. *Non-sensing GN&C flight hardware* includes micro-spacecraft GN&C subsystems, radiation-tolerant GN&C elements, aeroguidance and solar-sail control mechanisms, and advanced flight computers. Finally, *GN&C ground test facilities* include testbeds such as free-flying simulators, air-bearing facilities, crewed and uncrewed aerial vehicle (e.g., helicopters and UAVs) simulators, and atmospheric entry test platforms.

These technologies help meet a host of challenges posed by future NASA Planetary Science Division (PSD) missions, including operations in time-constrained highly dynamic environments, in the face of long round-trip light-times, long-lived missions, budgetary challenges, distributed spacecraft and spacecraft systems, autonomy requirements, complex fault responses, and stringent pointing requirements. Furthermore, these challenges are met in a wide variety of mission scenarios, including surface landing in high- or low-gravity, in high- or low-density atmospheres, encountering primitive bodies, working in extreme physical environments, on airborne planetary platforms, during multibody planetary tours, in proximity operations around small bodies, and during touch-and-go contact with low-gravity objects, among others.

This report includes a number of findings and recommendations, which are summarized below and derive from the discussions in the following sections.

1.1 Finding 1

Autonomous onboard GN&C: Advancement in spacecraft autonomous GN&C capability, i.e., the ability to manipulate spacecraft trajectory and attitude autonomously on board in reaction to the in situ unknown and/or dynamic environment, is required for next-generation SMD PSD missions to reach and explore scientific targets with unprecedented accuracies and proximities. Examples include autonomy for Mars Sample Return Lander EDL discussed in Section 3.1.1 and autonomy for Uranus Probe aerocapture discussed in Section 4.1.4.

Recommendation: Develop autonomous GN&C capability, with parallel investments in innovative architectures, innovative and optimized algorithms, advanced sensors and actuators, and system-level demonstrations with relevant physical dynamics and environment conditions. This includes improved capability for EDL (Entry, Descent, and Landing relevant to planets with atmospheres), and DDL (Deorbit, Descent and Landing relevant to planets without atmospheres); Aerocapture performance at Mars, the Ice Giants, and outer planet moons; formation flying for lunar, asteroids/NEO exploration and planetary protection; GN&C for small body proximity operations; and ascent vehicle GN&C and rendezvous & docking to support sample return missions.

1.2 Finding 2

New and advanced GN&C sensors: Innovation and advancement of onboard sensing capabilities are critical, taking advantage of the most recent breakthroughs in component technologies (e.g., autonomous robots, self-driving cars, etc.) and spaceflight-qualifiable computing elements for enhanced onboard instrument analysis capability.

Recommendation: Develop advanced GN&C sensors with direct relevance to future mission needs. Make advancement in individual sensors as well as in integrated sensor systems. With significant advanced computational capability and smaller, less power-hungry sensor components, integration of a few components can serve multiple purposes. GN&C hardware and systems for precision velocity and range sensing are needed to improve navigation accuracy for EDL and DDL. Efforts should be made to reduce the size/mass/power of terrain-relative sensors (cameras, lidar, altimeters, radars, etc.), improve radiation hardness, and lower component/system integration costs.

1.3 Finding 3

New and advanced GN&C algorithms: GN&C algorithm development is needed in parallel with advancements in hardware, software, and architecture. Examples include 6DOF coupled guidance algorithms for close-proximity operations (cf., Section 4.1.1), control algorithms for low thrust SEP spacecraft for outer planet exploration with increasingly large solar panels and lightly damped flex modes (cf., Section 4.1.1), and advanced flight control algorithms for future more capable Mars helicopters (cf., Section 4.1.3).

Recommendation: Develop algorithms for innovative solutions to GN&C challenges, e.g., fuel-optimal, real-time GN&C solutions, new techniques and approaches that enable much greater landing accuracy, and fusion of data from multiple sensor sources for superior estimation of spacecraft states. Emphasis should be placed to address situations with tight time constraints (e.g., responding to late-breaking navigation updates for improved Aerocapture), high dynamics (alternative/Skycrane-style planetary landings, rotorcraft dynamics), guided trajectories through atmospheres (hypersonic entry, EDL, Aerocapture), high disturbance environments (hovering over plumes on Enceladus, Titan probes/flybys, comet outgassing), maneuvering in close surface proximity (e.g., small body exploration), and integrated onboard 6DOF control of the trajectory and attitude of the spacecraft. To be most effective, algorithms should be developed in parallel with new architectures, hardware, and software.

1.4 Finding 4

Testing capabilities are critical and need to be improved. As more complex systems with stringent performance requirements are pursued, end-to-end system-level modeling, as well as testing and simulation are required to flight-qualify newly developed system-level capabilities achieved through incorporation of new technology elements.

Recommendation: Continue to advance integrated modeling and simulation at the mission capability level, with increasing fidelity that matches advancements in component technologies. Develop system-level demonstration systems, such as ground based end-to-end GN&C system testbeds, aerial field tests, sounding rockets tests, and free-flying-vehicle-based, closed-loop GN&C system tests.

1.5 Finding 5

There is substantial commonality in GN&C technology needs across missions. GN&C components and systems can be developed and deployed across multiple mission types more effectively and economically than point-design solutions engineered for individual mission scenarios.

Recommendation: Attention should be paid to GN&C *systems*, not just the individual algorithms, hardware, and software subsystems, because this will allow for reasoned cross-cutting trades across functions and missions. PSD can provide incentives in the structure of announcements of opportunity such that feed-forward of developments for one project to the next are maximized.

1.6 Finding 6

General onboard spacecraft autonomy: Onboard autonomous GN&C is a significant part of overall spacecraft autonomy. It is closely related to advancement in areas of onboard planning; re-planning; and fault detection, identification, and recovery.

Recommendation: GN&C technologists need to stay current with advancements being made in the related fields of general onboard autonomy and onboard planning; re-planning; and fault detection, identification, and recovery. This would be best achieved through regular targeted workshops where NASA GN&C technologists would invite leading technologists in other fields to explore technology-transfer opportunities.

1.7 Finding 7

Planetary Defense is a relatively new and important area described in the Planetary Sciences Decadal Survey to mitigate the threat from potentially hazardous Near-Earth Objects (NEOs) impacting Earth. Onboard GNC capabilities are needed that enable NEO flyby, characterization, target intercept, rendezvous, and kinetic impact/nuclear-based mitigation scenarios.

Recommendation: Develop precision terminal GNC algorithms and associated spacecraft systems for hypervelocity flybys/intercepts to enable accurate and reliable targeting of small NEOs at closure speeds of up to 20 km/s. Ion beam deflection and gravity tractor methods require GNC capabilities that enable the spacecraft to formation fly with the NEO, performing close, autonomous, and extended proximity operations to station keep at a predetermined distance from the target body. The onboard GNC system must also be tolerant of technical system faults and unexpected NEO physical characteristics including tumbling, outgassing, mass expulsion, and hazards from orbiting bodies/moons.

1.8 Finding 8

Advanced navigation technology for EDL/DDL: An important goal for future planetary exploration is to precisely land payloads while simultaneously avoiding landing hazards. Terrain Relative Navigation (TRN) is an important localization capability that provides a map-relative position fix that can be used to accurately target specific points on planetary surfaces. Hazard Detection and Avoidance (HDA) is an important landing function that uses data collected on board to identify safe landing sites in real time as the vehicle descends. As examples, TRN will be needed for Mars Sample Return EDL as discussed in Section 3.1.1, and HDA will be needed for the Dragonfly rotorcraft mission to Titan (cf., Section 5.2.4, Part IV of this report series).[4]

Recommendation: Develop algorithms and processes for TRN and HDA to improve EDL/DDL landing precision as well as to avoid large-scale surface hazard regions observed in reconnaissance maps. At lower altitudes and closer ground proximity, algorithms and processes for real-time map generation should be developed to support precision TRN and to enable HDA to avoid small-scale surface hazards while finding regions suitable for safe landing. Relevant special topics include the development of long-range lidars, the ability to land in the dark, illumination insensitive landmark matching, cross-modality feature matching (e.g., visible and SAR), and potentially a “fully autonomous” bolt-on type TRN sensor system that produces position/pose estimates without requiring inputs from the host spacecraft. For example, it could provide its own position/velocity information for initialization, produce its own attitude knowledge throughout, and run on its own stand-alone computational platform.

2 Spacecraft Onboard GN&C for Future Planetary Missions

Spacecraft *Onboard GN&C* is defined to be the path-planning, sensing, and control of the spacecraft to achieve desired spacecraft maneuvers and pointing. *Navigation* is defined to be determination of the vehicle’s position and velocity and calculations associated with the adjustment of that position and velocity to achieve a desired course. *Guidance and Control* (G&C) is defined to be the onboard manipulation of vehicle steering controls to follow the desired path while maintaining vehicle pointing both with the required precision. In many cases discussed here, this has to be carried out simultaneously by track navigation computations while maintaining vehicle pointing. Sensing and estimation are integral parts of onboard GN&C for in situ inertial, celestial, and target- or terrain-relative measurements and estimation of the spacecraft state.

Recommendations for future missions have been made in the National Research Council’s (NRC’s) *Origins, Worlds and Life 2023–2032*,[1] developed at the request of NASA Science Mission Directorate (SMD) Planetary Science Division (PSD). Technology investments need to be made in onboard GN&C in order to accomplish missions being proposed for the next decade. Specific recommendations have been made where the MSR and Dragonfly missions are designated for continuation, and the Uranus Probe and Enceladus Orbilander are designated as the highest priority new NASA flagship missions. In addition, New Frontiers 6 recommended mission themes were chosen as:

- Centaur Orbiter and Lander (CORAL)
- Ceres sample return
- Comet surface sample return (CSSR)
- Enceladus multiple flyby (EMF)
- Lunar Geophysical Network (LGN)

- Saturn probe
- Titan orbiter
- Venus In Situ Explorer (VISE)

Mission themes chosen for New Frontiers 7 include all non-selected mission themes from the NF-6 list above, with the addition of:

- Triton Ocean World Surveyor

Planetary Defense has also become an important part of the OWL report.[1] The focus is to understand and characterize Near Earth Objects (NEOS) and to develop methods to defend against the threat from these potentially hazardous objects impacting Earth. In addition to the above, the OWL report discusses a variety of other interesting mission themes with assessments of their relative scientific interest, technology readiness, and time criticality.

As well as the above missions that were specifically called out by the Decadal Survey for the next decade, technology developments are also needed for missions in the competitive Discovery program where targets and science objectives are established by the Principal Investigators. Technology developments are also needed to enable the directed missions that will be formulated by the next Decadal Survey seven years from now. Anticipating these many diverse requirements, the National Research Council's (NRC's) *Origins, Worlds and Life 2023–2032*,[1] identified a set of technologies to be "advanced in this decade and beyond." Spacecraft onboard GN&C does not appear explicitly in that list but it is an enabling element of many of them: Entry\Deorbit Descent and Landing Systems; In Situ Mobility (Aerial/Surface); Launch, Cruise and Encounter operations, Autonomy; and Technology System Engineering and Integration. The OWL report also identifies several disruptive technologies with a bearing on GN&C including Pulsar Navigation; Automotive Electronics for driver-less cars; Quantum Computing and Artificial Intelligence/Machine Learning. This report is guided by the OWL requirements and attempts to explore them in much greater depth.

For each individual mission, there are typically challenging mission scenarios that must be addressed, and that require special GN&C capabilities to be exercised to have a successful mission. To reach and explore the new scientific targets of SMD PSD interest, advances in GN&C capabilities are needed to address the following scenarios:

- Surface landers
    - Surface lander on targets with high gravity and atmosphere (type 1)
    - Surface lander with significant gravity and no atmosphere (type 2)
    - Surface lander on low-gravity, small-body targets (type 3)
- Proximity operation about low-gravity, small-body targets
- Sample-return missions
- Ascent, autonomous rendezvous and docking (AR&D)
- Multiple-target planetary tours
- Planetary orbiters
- Formation flying and spacecraft swarms
- Aerial Missions

The recommended PSD missions from the Decadal Survey are shown associated with their corresponding GNC-relevant mission scenarios in Table 1. Each of the mission scenarios creates their own specific challenges for GN&C. However, it is worth mentioning that there are certain fundamental drivers that are common to all missions that include

- Long round-trip light time
- Time constrained in situ operations
- Unknown dynamic environment with limited prior information about destination
- Flight and mission system fault conditions
- Mission longevity
- Long-duration, limited communication/data
- System resources are constrained and tightly coupled
- No opportunity for maintenance

These drivers apply variously to some or all of the above GNC-relevant scenarios outlined above and together with other more specific challenges will drive the development of GN&C technology across a wide range of functions. The key mission scenarios and their corresponding enabling GNC capabilities are discussed in Chapter 3. The supporting technologies needed to realize these GNC capabilities are discussed in Chapter 4.

Table 1. Recommended PSD missions from the Decadal Survey and their corresponding GNC-relevant mission scenarios.

	Planetary Orbiter	Surface Lander*			Sample Return	Multiple Target Tour	Aerial	Proximity Operations	AR&D	Formation Flying
		1	2	3						
Mars Sample Return	✓	✓			✓		✓		✓	
Dragonfly	✓	✓					✓	✓		
Uranus Orbiter and Probe	✓	✓								
Enceladus Orbilander	✓		✓					✓		
Centaur Orbiter and Lander (CORAL)	✓			✓				✓		
Ceres sample return	✓		✓		✓			✓		
Comet sample surface return				✓	✓			✓		
Enceladus multiple flyby (EMF)						✓				
Lunar Geophysical Network			✓							
Saturn probe	✓	✓								
Titan orbiter	✓									
Venus In Situ Explorer		✓					✓	✓		
Triton Ocean World Surveyor	✓					✓				
Europa Lander		✓								
Planetary Defense				✓		✓		✓	✓	✓

*Surface Lander sub-columns: 1 – high gravity with atmosphere, 2 – high gravity, no atmosphere, 3 – low gravity, no atmosphere

3 Future Missions Scenarios Requiring Advanced Onboard GNC

This section presents scenarios for missions called out in the Planetary Science Decadal Survey[1] and discusses relevant GN&C capabilities needed to support these scenarios.

3.1 Surface Landing Missions

3.1.1 Landing on Mars

Relevant future missions: Mars Sample Return (MSR), Mars Life Explorer, future Mars rovers, and future Mars aerial missions

For a planetary body with an atmosphere, Entry, Descent, and Landing (EDL) is the process of delivering a vehicle initialized at a point above the atmosphere down to the surface of the body and landing safely.[5–19] EDL generally consists of three phases of flight comprised of Entry Hypersonic Flight, where the vehicle is guided to the target in the presence of large decelerations and heat dissipation; Descent Supersonic Flight, where the vehicle hands off to alternative deceleration methods such as opening parachutes and firing jets; and finally the Landing Subsonic Flight, consisting of sensing the surface, configuring the vehicle for landing, and then touching down typically using thruster-based control. The analogous process for planetary bodies that do not have atmospheres is denoted as Deorbit, Descent, and Landing (DDL). An important potential option for airships is to mitigate landing completely by performing deployment in midair, which is denoted here as Entry/Descent/Deploy (EDD).

Figure 1. A Phoenix-derived Mars Sample Return (MSR) concept shown performing precision landing on Mars in an artist's concept. (credit: https://astrobiology.nasa.gov/missions/phoenix/)

Performing EDL on Mars requires a fully autonomous GN&C capability with linked attitude and trajectory guidance driving a very-high-frequency closed-loop controller due to a highly dynamic environment, high gravitational forces, and atmospheric perturbations (Figure 1). These systems will be increasingly linked to sensors and actuators including IMUs, terrain-relative navigation sensors, hazard-detection sensors, altimeters, velocimeters, engine throttles, and other control mechanisms as the accuracy demands continue to intensify with each successive Mars landing mission. For example, the current Mars Sample Return Lander Platform has a challenging accuracy requirement of 60 meters relative to the desired landing target.

On February 18, 2021 the Mars 2020 Mission successfully landed the Perseverance rover within a 7.7 x 6.6 km landing ellipse on February 18, 2021. The EDL system consisted of a 70° sphere cone aeroshell, a deployment range trigger, an Apollo-based entry guidance that commanded bank angle reversal maneuvers, a camera-based Terrain-Relative Navigation (TRN) system based on the JPL Lander Vision System (LVS), and a JPL Doppler Radar for velocity and range. The TRN function fused camera images and IMU data for precise position localization relative to a known predetermined reconnaissance map generated from Mars orbiter imagery. The system enabled landing at a location identified as safe within the prescribed reconnaissance maps.

Improvements in landing accuracy and delivered mass for next-generation Mars missions will be enabled by improved initial attitude knowledge at atmospheric entry, advanced atmospheric entry G&C technologies, advanced vehicle deceleration technologies, and new parachute deployment trigger and G&C strategies. In combination with improved pre-entry navigation and intelligent use of nano-g accelerometers, this can lead to dramatic targeting improvements at landing for inertially-navigated solutions. Further improvements in landing precision will be enabled by the development of landmark-based navigation with terrain-relative navigation (TRN) for determining the offset to the target, and using this knowledge in conjunction with state-based deployment triggers and commanded trajectory deflections to minimize vehicle offsets from the target. On the Mars 2020 mission, the divergence from the desired landing site at the end of the atmosphere entry phase is relatively large at 4 km due to uncertainties in atmospheric density and wind velocity. Current improvements to the EDL Concept of Operations that use TRN prior to parachute deploy and an improved parachute deployment algorithm cut this error in half, to 2 km, which is the current predicted performance of the Mars Sample Return Platform. The subsequent controlled, powered, descent phase can further bring down the final landing error to about 60 m.

When pre-landing surveys of the terrain are inadequate to guarantee safe landing, which might be the case at Titan and Venus, hazard detection and avoidance (HDA) will be increasingly necessary for autonomous safe landing. This is true for the Dragonfly rotorcraft mission to Titan as discussed in Section 5.2.4 of Part IV of this report series.[4] Thus, some combination of improved pre-entry navigation, accelerometry, TRN, fuel-optimal, large-trajectory, divert guidance (path planning), and HDA are needed to realize landing performance improvements. Leveraging these GN&C capabilities, an almost arbitrary landing accuracy can be achieved within limits constrained only by terminal descent fuel capacity. Such GN&C capabilities offer the promise to reliably position the landed asset directly in a region of high science interest in the future.

3.1.2 Landing on Titan and Venus

Relevant future missions: Venus In- Situ Explorer, Dragonfly

Titan and Venus, though dramatically different in size and surface acceleration, share a similar ratio of atmospheric density (proportional to entry drag) to gravitational potential. Thus, entry trajectories, after deceleration to subsonic speeds, are very slow with simple parachutes providing descent paths of many tens of minutes' duration. If precision guidance is necessary during this phase, there is generally ample time to accomplish it through control surfaces or mechanisms on the parachute or balloon. The navigation of such descent trajectories is done by leveraging imaging-based TRN capability, or radiometric methods involving one-way data from Earth and/or from an orbiting relay craft (Figure 2). As an example, the TRN and HA systems for the Venus Flagship Mission (VFM) are discussed in detail in Appendix B.2.8.2.5 of Gilmore, et. al. 2020.[20] Low-speed sub-sonic descents are particularly favorable for the deployment of rotorcraft vehicles, such as are being baselined for

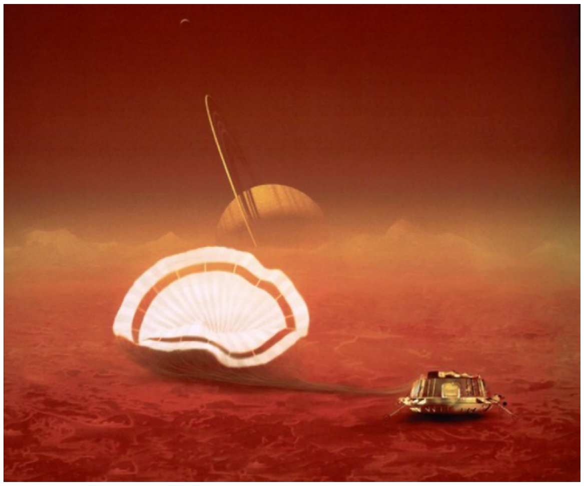

Figure 2. Artist rendering of a Titan probe landing on the surface. (credit: ESA 2005)

the Dragonfly mission to Titan, and may play a role in the proposed VFM.[21] Additionally, exploration vehicles to Titan and Venus must be able to survive extremes of temperature.[21,22] Survival duration time on the surface of Venus is typically limited due to the extremely high temperature and the inability to reject heat to the environment to keep the spacecraft within physical operating limits. Improving vehicle survivability is an important technology area to make Venus surface missions more practical.

3.1.3 Landing on Bodies with Significant Gravity and No Atmosphere

Relevant future missions: Enceladus Orbilander, Ceres Sample Return, Lunar Geophysical Network, Lunar Endurance-A, Human Lunar Exploration Systems, Unmanned Lunar landers (e.g., South Pole Aitken Basin Sample Return), Europa Lander

Deorbit, Descent, and Landing (DDL) Robotic landing on large surfaces without an atmosphere and without significant gravity (greater than 0.25 m/s^2 surface gravity), poses different challenges compared to landing on Mars, Titan, or Venus. For example, it can be easier than Mars landings in the sense that atmospheric uncertainties are not present and the target site is typically visible starting from very high altitudes with no entry “plasma phase” to block the view. However, it can be more challenging from the aspect of larger down-track travel near the surface, where very short vertical terminal descent periods (due to the larger gravity) may stress TRN map needs, and the existence of permanently shadowed regions may stress or render passive TRN solutions unusable. An example is the challenging concept of operation (CONOP) required for landing at the Lunar South Pole. Landmark-based autonomous navigation with TRN and HDA is still necessary to reach critical landing sites of high scientific interest, but they still may be surrounded by terrain hazards, which may not be fully characterized by orbital data and only encountered first during the actual DDL event itself (Figure 3). Reconnaissance of landing sites prior to landing is generally required for all current TRN techniques, however a stretch-goal for long-arc development of TRN technology should include DDL CONOPs that do not require such reconnaissance. Alternative approaches that do not require reconnaissance prior to landing are also under development.[23] For descent/landing regions that are not illuminated, “active” TRN is generally required, which leverages lidar altimetry and makes use of special techniques such as terrain contour matching (TERCOM). Additional discussion of TERCOM can be found in the context of localizing an aerial platform at Venus in Part IV of this report series.[4]

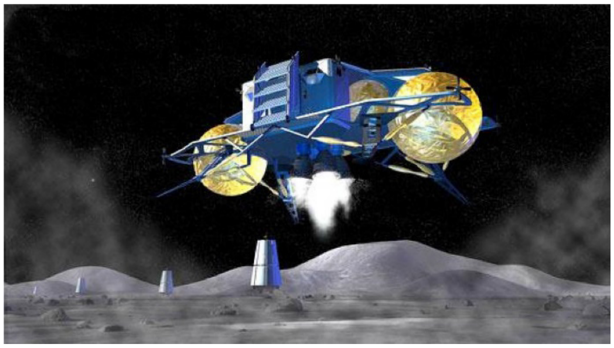

Figure 3. An artist's interpretation of NASA's conceptual heavy cargo-carrying lunar lander, shown re-supplying bases on the Moon. (credit: NASA)

3.1.4 Landing on Low-Gravity, Small-Body Targets

Relevant future missions: Centaur Orbiter and Lander (CORAL), Comet Surface Sample Return, Mars moon exploration, planetary defense missions

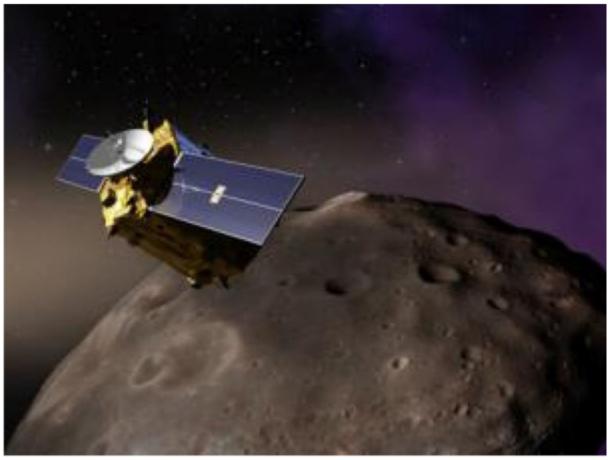

Figure 4. An artist's illustration shows the Next Gen NEAR spacecraft approaching a near-Earth object. A concept based on the successful Near Earth Asteroid Rendezvous mission, Next Gen NEAR could serve as a robotic 'precursor' for a human visit to a near-Earth asteroid. (credit: Applied Physics Lab)

Key characteristics for landing on small-body targets (cf., Figure 4) are their much lower gravity and lack of atmosphere. The low gravity allows for 1) longer timelines for surveillance and characterization of the target site, 2) gradual descent to the target, 3) multiple landings or contacts and ascents, and 4) aborting and restarting during critical activities. The lack of atmosphere removes uncertainties due to atmospheric and wind effects, and provides a clear scene for landmark-based autonomous navigation with TRN and closed-loop GN&C. There is an exception in the case of certain asteroids and comets that produce outgassing/atmospheric events that at times can be substantially obscuring. Additionally, the OSIRIS-REx mission discovered that small "rubble pile" asteroids like Bennu can have materials lifted from the surface in discrete outbursts or even excited by near-surface spacecraft thrusting.[24]

An important attribute of these missions is the lack of a priori information about the target body. In particular, detailed maps will be required to undertake the landmark-based navigation as well as detailed gravity models. In general, this requires an extensive campaign to survey the body with systematic reconnaissance flights, including special orbits and low-altitude flybys, to gather enough data to create sufficiently detailed maps. This map-generation effort is supported by a ground-based process that can be highly human labor and computationally intensive. An area for future development is the streamlining of this map-generation effort, and possibly the promotion of certain elements to be performed on the spacecraft itself to support near-real-time autonomous operations.

3.2 Proximity Operation about Low-Gravity, Small-Body Targets

3.2.1 Proximity Operations and Sampling

Relevant future missions: Comet surface sample return, Centaur Orbiter and Lander (CORAL), Mars moon exploration, planetary defense (e.g., NEO rapid-response flyby reconnaissance missions)

Multiple options for proximity operations and sampling are available for small-body targets, (cf., Figure 5). Such options include Touch-And-Go (TAG) sampling; open-loop close flyby; and harpoons, darts, and others.[25–41] These share, in various combinations, phases of operation including approach, descent, hovering, ascent, pursuit, and capture. Mission design capabilities that support the design of trajectories for small body targets are discussed in Section 2.3 of Part I of this report series.[2]

Touch-An-Go (TAG) Sampling Approaches

Figure 5. Approaching the Near-Earth Object (NEO), an astronaut crew prepares airbag plus sensor docking and securing system prior to close approach or surface docking. (credit: DigitalSpace)

It is useful to discuss TAG first. TAG entails a "soft" and short landing operation, where a sampling probe, rather than the entire spacecraft, makes contact with the target body.[25] TAG requires a combination of onboard landmark-based autonomous navigation with TRN, combined six-degree-of-freedom (6-DOF) G&C to sense external forces and react to them, and executive-level autonomy.

The Japanese small body mission Hayabusa to asteroid Itokawa,[26] and the successor Hayabusa2 mission to asteroid Ryugu,[27–29] both used the novel method of deploying target markers with retroreflectors onto the surface of their target asteroids. These reflectors were used as landmarks to aid navigation during proximity operations. TAG events were performed on both missions. During each TAG event, a small bullet from a pellet gun was fired into the asteroid's surface, from which the ejected fragments were collected with a sampler horn. Although the sampling mechanism did not work exactly as intended for Hayabusa, thousands of Itokawa particles were still collected from the container and successfully returned to Earth in June 2010. The Hayabusa 2 spacecraft arrived at Ryugu in June 2018. It deployed a series of landers and collected multiple samples from the asteroid. It performed TAG sampling twice, once in February 2019 and again in July 2019, using the pellet gun approach described above. The second sampling event was scientifically notable because earlier in the mission the spacecraft had fired a compact kinetic impactor to remove the asteroid surface regolith locally and create an artificial crater, which exposed pristine subsurface material.[30] This allowed the second sampling event to effectively retrieve a sample from beneath Ryugu's surface. In December 2020, Hayabusa2 delivered its asteroid samples to Earth.

NASA's OSIRIS-REx spacecraft performed a successful TAG sequence in October 2020 at the asteroid Bennu.[31,32] In this case the sampler head at the end of a sampling arm contacted the surface for about 6 seconds. During this time a jet of nitrogen gas fluidized the surface and drove particles into the collection chamber. The OSIRIS-REx samples are planned to arrive back to Earth by September 2023.

Other Sampling Approaches

In addition to TAG, there are other types of proximity operations and surface approaches that can be considered: a close flyby, a harpoon type, and an impactor type.

A close flyby approach consists of an open-loop-controlled trajectory typically commanded from the ground, which targets a close-proximity flyby of the small body.

A harpoon approach keeps the spacecraft hovering at a further distance than does TAG and uses a longer, flexible appendage or tether from the spacecraft to anchor and retrieve the sample. This method[40,41] may be simpler from a GN&C standpoint, as it reduces surface transmission forces and torques to the spacecraft.

Finally, an impactor collection approach involves collecting cored samples from the surface with a device such as a mechanical dart and then retrieving the ejected sample canister via

Autonomous Rendezvous and Docking (AR&D) functions. Coring darts can be tethered or free. In either case, concepts for ejecting the dart from the surface include using a spring or air pressure. With a tethered dart, collection is accomplished by simply reeling in the dart, but the operation would involve more mass and hardware complexity than with a free-flying dart and would likely require the spacecraft to be closer to the target. With a free-flying dart, the sample collection is via tracking and rendezvous and capture, as for MSR. This entails algorithmic and computational complexity but allows for smaller mass, simpler mechanisms, and may allow a much greater stand-off distance from the surface of the body (in this case most likely a comet), providing substantial safety. Tracking of the dart sample would be via optical and radiometric measurements.

Autonomous Functions

Small body missions also present important autonomy challenges, especially for fault detection, isolation and recovery (FDIR) functions. For scenarios where the spacecraft is close to the surface of the body, a few moments of faulty attitude maintenance can end the mission, driving a solar array into the regolith or breaking an appendage. Therefore, more effective and reliable FDIR logic must be incorporated into the executive functions to provide varying levels of fallback, regroup, recovery, or simple escape from the region of danger. Such logic may also, in the case of active comets, need to assess the danger associated with the active body itself during outgassing events.

Hazard Avoidance

Hazard avoidance (HA) is also a critical onboard capability needed to avoid contact with obstacles lying in the vicinity of the landing site. HA is most simply implemented by choosing a landing site that is “safe” in the sense of being clear of obstacles over a region the size of the expected landing error ellipse. Unfortunately, the existence of such a safe landing site may not be known beforehand, and only understood after surveying the body surface in sufficient detail. This was the case for the OSIRIS-REx mission, where the surface of Bennu was found to be much rockier than expected with the largest hazard-free sites no larger than 8 meters in radius, compared to an expected 24-meter error ellipse. Accordingly, the project switched to baselining an onboard natural feature tracking approach instead of lidar, in order to reduce the size of the landing error ellipse in support of TAG. An alternative future method would be to carry an autonomous onboard Hazard Detection and Avoidance (HDA) capability that can make a real-time assessment of local terrain and divert to a safe nearby landing site in the vicinity of the original desired landing site if needed.

3.2.2 Small Satellites

Relevant future missions: NASA SIMPLEx (e.g., Janus, EscaPADE, Lunar Trailblazer)

The opportunities and capabilities of small satellites have grown considerably in the last decade. Originally the sole domain of universities, small satellites are increasingly being used as a cost-effective, high-risk, science platform, both for Earth orbit and beyond. A pathfinder for interplanetary small satellites was demonstrated by JPL’s MarCO spacecraft, which successfully launched along with Mars Insight and provided communications relay for the lander. Small satellite mission concepts now range from single satellite to multi-spacecraft constellations (e.g., BCT’s TROPICS satellites) and formations. They are targeted for a wide range of trajectories, from LEO, GEO, Lagrange points, as well as interplanetary.

Over the past 10 years, a game changer has been the emergence of profitable commercial industry involvement that strongly supporting the CubeSat form factor. Supported by NASA and

Defense industry grants, these commercial partners have expanded from focusing on single subsystem product manufacturing to suppliers of the whole spacecraft bus. Industry, such as Blue Canyon Technology, Aerospace Corporation, and Tyvak Inc, can supply the spacecraft bus, the GN&C subsystem, and a variety of ever-increasing power and pointing capabilities. This has allowed governmental organizations to focus on the mission and the science. The NASA-sponsored CubeSat Launch Initiative, which started in 2010 and was a competitive program that provided the launch free to the selected payloads, was also instrumental in increasing the opportunities for these cost-limited missions. Similar programs exist in other agencies, such as ESA and the Canadian Space Agency. Commercial industry, such as PlanetLabs, have also used the small satellite platform as a tool to obtain their business model.

As technology continues to advance, small satellite platforms are becoming increasingly more capable. High-precision pointing capability has previously been limited largely due to the lack of affordable and low-SWaP star trackers, low-drift IMUs, and sufficiently quiet reaction wheels. However, industry is catching up. There are now flight-ready miniaturized reaction wheel designs having reduced imbalances, improved MEMs gyros, and miniaturized star trackers approaching 1 arcsecond accuracy. Current projects in development focus on increasing the pointing capability and onboard autonomy. These capabilities will allow small satellites to become self-contained probes with streamlined ops interfaces.

3.2.3 Asteroid Tour

Relevant future missions: Centaur Orbiter and Lander (CORAL), planetary defense missions

An asteroid tour mission that retrieves samples requires the full range of small-body GN&C capability, including autonomous low-thrust operation, surface operations such as TAG, TRN, and automated science mapping. Currently, such autonomous capabilities for onboard GN&C implementation largely remain a challenge. Enhancements would include path-planning and trajectory optimization to allow for special low-altitude operations, propellant conservation, and reduction of operations staff and costs during proximity operations. Multi-asteroid tours would, without onboard autonomous GN&C, have complex periods of electric propulsion operations. With automated GN&C, all operations of the propulsion periods, including turns to attitude and operation of the engines, can be automated. Even trajectory retargeting can be completely automated with onboard path planning. Advanced GN&C-specific imagers, and integrated GN&C instruments and software, will provide cost savings for this and other missions. Altimeters will most likely be required to increase the reliability of the TAG operations, and high-precision accelerometers will increase the accuracy of such operations. Additional discussion of multiple encounter tour design is provided in Section 2.2 of Part I of this report series.[2] There it is explained that design/redesign of low-thrust trajectories can be difficult and computationally intensive, even on the ground with humans in the loop and might in some applications present special challenges for obtaining onboard solutions.

3.3 Sample Return Missions

Relevant future missions: Mars Sample Return, Ceres Sample Return, Comet Surface Sample Return

Figure 6. Artist's illustration of a sample-carrying robotic Mars Ascent Vehicle (MAV) launch from Mars during a Mars Sample Return Mission. (credit: NASA/JPL-Caltech).

Sample-return missions from the different targets in our Solar System may take one of several forms, requiring a wide range of possible GN&C technologies. As currently envisioned (cf., Figure 6), Mars Sample Return (MSR) will launch an Orbiting Sample (OS) canister into Mars orbit from a surface lander using a Mars Ascent Vehicle (MAV). An orbiting Earth Return Orbiter (ERO) will perform an Autonomous Rendezvous and Capture (AR&C) of the OS using a combination of ground-in-the-loop and onboard autonomous GN&C.

For target bodies with small gravity wells, such as asteroids and comets, the sample return architecture might use a Touch-And-Go (TAG) operation that is essentially a very soft landing. Sample collection is immediately followed by ascent. The challenge is finding a safe location on the target body to execute the TAG without parts of the spacecraft being damaged by contact with the surface. This was the approach taken by the OSIRIS-Rex mission at the asteroid, Bennu.

Sample return missions from larger planetary bodies e.g., the dwarf planets Ceres, and Vesta, or the Martian moons, may require an onboard navigation ability to maintain a constant thrust trajectory with minimal intervention from the ground. Others may use dart-like projectiles to mechanically take a sample and eject it back toward the waiting spacecraft, requiring an MSR-like AR&C operation. Some have proposed micro-sample-return missions to NEOs or other asteroids, or even to Martian moons, where MiniSat or CubeSat-class vehicles would return samples to the Earth or Moon via micro-electric propulsion.

The return leg of a sample return mission begins with the ascent from the target body after the in-situ and sample collection phase. Depending on the size of the target body's gravity field and the presence or lack of an atmosphere, the mission architecture may be more mass efficient to include a separate ascent vehicle whose primary purpose is to get the collected samples off the surface of the target body instead of landing the entire spacecraft with all the equipment to perform the Earth return interplanetary cruise and Earth entry. Once the ascent vehicle has achieved orbit, the Earth return vehicle must locate and rendezvous with the ascent vehicle (or more likely capture a separate orbiting sample canister deployed from the ascent vehicle as in the MSR architecture) before beginning the interplanetary cruise back to Earth.

A critical GN&C challenge for the ascent vehicle is the availability of low-mass, navigation-grade inertial sensors. In most sample return architectures, the design is penalized twice for the ascent vehicle mass since it must be carried and landed by the primary lander during EDL before being used for ascent. This makes it especially important to minimize the mass of the ascent vehicle's GN&C subsystem. At the same time, the GN&C sensors must be accurate enough to guide the vehicle to the intended orbit. Initialization of the inertial sensor before ascent is also required either by gyroscopic compassing or using a star tracker, which must also be low mass.

Rendezvous with the OS starts by solving for the canister's orbit. If the Earth return vehicle can track the OS using a camera during its launch, the OS's subsequent orbital uncertainties can be reduced. Multiple observations of the ascent vehicle using a narrow-angle camera, perhaps over a period of several months, may be required to determine its orbit with sufficient accuracy to design rendezvous maneuvers, to get the Earth return vehicle within range of the terminal rendezvous sensors used by the onboard GN&C to perform the terminal rendezvous, and to get the OS within mechanical capture range. Radio Direction Finders (RDFs) on the OS and/or ascent vehicle might also be useful in this context. Light-time delays will likely require terminal rendezvous and capture to be performed autonomously to provide closed-loop 6DOF relative control and for timely fault detection and response.

3.4 Multiple-Target Planetary Tours

Relevant future missions: Enceladus Multiple Flyby, Triton Ocean World Surveyor (Neptune Orbiter), and Europa Clipper

A multi-target solar-system tour (e.g., of asteroids) is likely to be a low-thrust mission, such as is occurring with Lucy, and require some onboard ability to cope economically with the intense activity of electric propulsion over long cruise times (cf., Figure 7). If the tour is of a multi-moon system of one of the gas giants, autonomous path planning and targeting will be necessary to accurately target mission-critical keyholes that are typically low-altitude points above the moons. To achieve the necessary accuracy, landmark-based autonomous navigation with TRN will be required. To increase data return and at the same time reduce downlink requirements, autonomous systems to plan, schedule, implement, and reduce science data linked to onboard GN&C will be advantageous. Additional discussion of multiple encounter tour design, and outer planet tour, is provided in Sections 2.2 and 3.2.2, respectively, of Part I of this report series.[2]

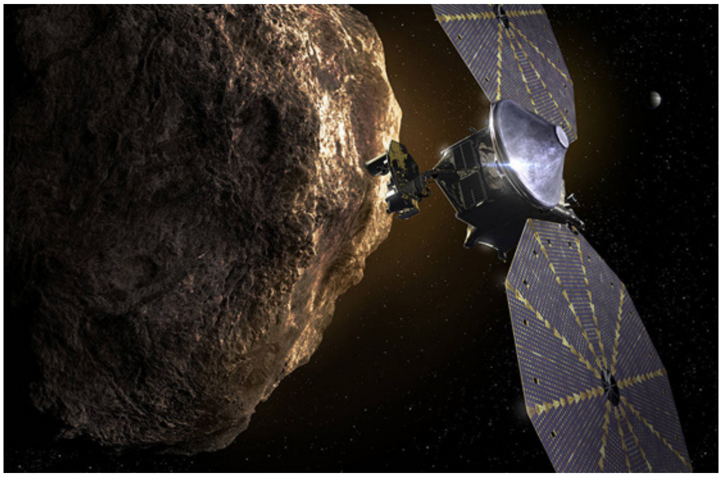

Figure 7. This illustration shows the Lucy spacecraft passing one of the Trojan Asteroids near Jupiter. (credit: Southwest Research Institute)

3.5 Planetary Orbiters

Relevant future missions: Venus In-Situ Explorer, Uranus Orbiter and Probe, Enceladus Orbilander, Titan Orbiter, Triton Ocean World Surveyor (Neptune Orbiter), Europa Clipper, Saturn Probe

Although planetary orbiters have been successful without extensive autonomous onboard GN&C, future missions with more demanding requirements will require such advanced systems. Using landmark and TRN based autonomous onboard GN&C, orbiters can maintain their own orbits or hover over a desired terrain feature to sample plumes or jets. At Mars and other bodies with atmospheres, autonomous aerobraking could reduce the overall mass of the spacecraft by considerably reducing the amount of propellant required to achieve the insertion maneuver. Autonomous aerobraking systems are closely related to autonomous onboard GN&C systems. Autonomous navigation, combined with automated event planning and sequencing, will greatly aid the mapping of bodies, the high-resolution targeting of specific locations, and even the identification and targeting of newly discovered features of scientific interest.

Often a planetary orbiter is not conceived in isolation, but is designed as part of a multi-segment exploration mission containing other supporting elements. A representative example is shown in Figure 8 for a Venus Flagship Mission concept involving an Orbiter, Lander, variable-altitude Aerobot, and two Small Satellites (SmallSats).[43] For missions that are composed of an orbiter and a lander/probe, the orbiter GN&C subsystem needs to be robust to the release of the lander/probe, and may need to be capable of performing coordinated operations with the lander/probe such as making observations or providing a communication link. For missions to far away celestial bodies (e.g., Uranus) with long cruise phases, the GN&C hardware needs to be reliable over long lifetimes (~20 years).

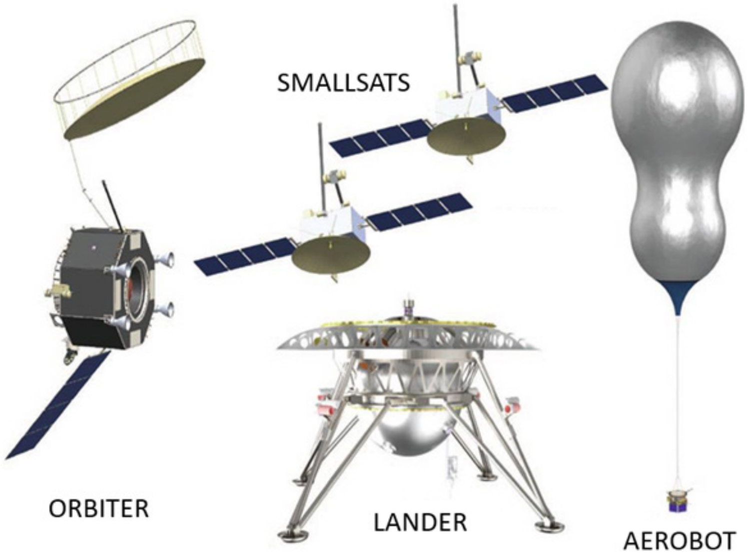

Figure 8. Multi-segment exploration elements for notional Venus Flagship Mission concept. (Adapted from NASA VFM Decadal Study Final Report, August 2020).

For orbiting or flybys of planetary targets with high radiation (e.g., Europa), innovative GN&C sensor/actuator technologies and shielding approaches need to be augmented with algorithms that can maintain healthy GN&C solutions in the presence of radiation-induced hardware anomalies. System-level trades of individual hardware performance, integrated algorithmic and system design solutions, and traditional shielding options will lead to optimized flight system and mission-level design for these very challenging missions.

For orbiters with tight pointing requirements, and/or comprised of large flexible appendages (solar arrays, radar antennas, magnetometers, etc.) and/or moving mechanisms, the GN&C subsystem needs to have sufficient control authority to provide fine pointing capability. This may require vibration isolation, multiple pointing stages, and advanced multi-input, multi-output, distributed and hierarchical control and estimation algorithms.

3.6 Formation Flying and Spacecraft Swarms

Relevant future missions: Contemporaneous spatially-distributed measurements (e.g., magnetosphere studies, gravitational field mapping, atmospheric science based on radio occultation) and multi-spacecraft synthetic apertures.

The ability to coordinate multiple spacecraft to achieve a common goal is beneficial for many planetary science applications.[44–74] Due to this report's emphasis on onboard GN&C, more traditional constellations where each spacecraft is managed individually with ground in the loop and with no relative measurements or control will not be discussed. Mission design capabilities that support the design of multiple-spacecraft trajectories are discussed in Section 2.5 of Part I of this report series.[2]

Two-spacecraft formations are the most common and Earth, Astrophysics and Heliophysics missions can provide lessons learned for Planetary missions. One application is rendezvous, proximity operations, and docking (RPOD), as demonstrated by Orbital Express and the Prototype Research Instruments and Space Mission Technology Advancement (PRISMA).[44,45] It is also the focus of the planned On-orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1)[46] and the planned CubeSat Proximity Operations Demonstration (CPOD).[47] Note that the RPOD application has intersection with the sample capture required to retrieve the orbiting sample in support of the Mars Sample Return mission. Other applications include interferometric synthetic aperture radar (InSAR), as performed by the TerraSAR-X add-on for Digital Elevation Measurement (TanDEM-X)[48,49]; gravimetry, such as the Gravity Recovery and Climate Experiment (GRACE)[50,51] for Earth gravity mapping, and the Gravity Recovery and Interior Laboratory (GRAIL)[52,53] for Lunar gravity mapping; virtual reconfigurable instruments such as the Project for Onboard Autonomy 3 (PROBA-3),[54,55] which is a near-term planned external solar coronagraph helio-physics mission comprised of a coronagraph and occulter spacecraft; and proximity operations with an uncooperative or defunct spacecraft, as demonstrated by the Autonomous Vision Approach Navigation and Target Identification (AVANTI) experiment.[56,57]

Small formations with more than two spacecraft are more challenging to implement and are therefore less common. However, they lend themselves to several kinds of contemporaneous spatially-distributed measurements and sampling of particular relevance to planetary missions. Applications include magnetosphere sampling (e.g., the Magnetospheric Multiscale [MMS] Mission,[58] which in principle could be similarly implemented at Mars or Venus) and atmospheric characterization, through direct measurements and sampling or, for instance, radio occultations. Another multi-spacecraft example is the MOSAIC mission—a constellation of ten Mars spacecraft coordinated to perform Mars climate science, which was studied as part of the Planetary Science Decadal Studies program.[59] Going further, a cluster is often defined as a formation with tens of spacecraft but with relaxed control requirements. In contrast, a swarm is a formation with similarly relaxed controlled requirements, but containing hundreds to thousands of typically lower-capability and generally less expensively manufactured spacecraft. Swarms can be used, for example, to synthesize large radio frequency apertures and sensor webs to probe planetary magnetic fields, or to "coat" a comet with distributed sensing.

In recent years, the cost of access to space has been reduced by an increasingly dynamic Low Earth Orbit (LEO) economy, the availability of widely accepted standards (e.g., the CubeSat form factor convention), and the availability of a large number of low-cost commercial-off-the-shelf (COTS) components and buses. Thanks to this trend, some formation flying and swarm technology demonstrations have been flown successfully in LEO (e.g., Can-X 4/5, PRISMA),[60] and many others are being planned (e.g., the swarm technology demonstrator Starling[61]). Planetary formation flying mission concepts will benefit from the risk and cost reduction brought about by these missions. Nevertheless, formation flying for planetary missions can be expected to remain more challenging than for LEO applications, as it inherently requires more onboard autonomy and must function without Global Navigation Satellite Systems (GNSS), or other satellite constellation that provides positioning, navigation, and timing (PNT) services.

An important emerging planetary application of small formations requiring two or more spacecraft is that of gravitational field mapping. For example, the Gravity Recovery and Interior Laboratory (GRAIL) mission listed above, was a lunar science mission that performed high quality gravitational field mapping of the Moon to determine its interior structure.[62] Implemented with two spacecraft, each spacecraft transmitted and received telemetry from the other spacecraft and Earth-based facilities. By measuring the change in distance between the two spacecraft, the gravity field and geological structure of the Moon was obtained. More generally, gravity mapping can be performed with formations having more than two spacecraft by using cross-links and measuring pairwise relative distances.

Another important planetary application of small formations is for the investigation of planetary atmospheric structure through the use of radio occultations (RO). RO science is typically performed by transmitting phase-stable radio signals from a single spacecraft orbiting or flying past a planet, which are then received at an Earth-based ground station. Changes in the phase and/or amplitude of the radio signals are used to infer properties of the planet's intervening atmosphere. Radio occultation investigations have been designed to measure pressure, temperature, and density profiles of the Mars' lower atmosphere and ionosphere with high vertical resolution. Importantly, the "spacecraft to Earth" link required for RO processing can be replaced by inter-satellite links between two or more orbiting spacecraft. Here, the higher signal-to-noise ratio associated with using inter-satellite links, compared to a link to Earth, decreases the design demands on the instrumentation. Ao et al. demonstrated the ability to acquire crosslink occultation measurements at Mars making use of the current Odyssey and MRO orbiting assets.[63] Focusing on smallsats, the Mars Cube One (MarCO), was the first spacecraft built to the CubeSat form factor to operate beyond Earth orbit for a deep space mission.[64] Two of the MarCO spacecraft were built and launched for redundancy. In principle, a future mission comprised of two or more small spacecraft similar to MarCO could be used to perform RO science for further understanding the Mars atmosphere.[65] This notion can be generalized to other planetary bodies as well. The Venus Atmospheric Science & Communications Opportunity (VASCO) mission has been proposed to carry out RO science utilizing two small spacecraft equipped with software-defined radios, to explore the atmosphere of Venus.[66] In a related effort, the Cross-link Radio Occultation measurements of the Venus Atmosphere (CROVA) mission proposes to study the Venus atmosphere using three small satellites comprised of one main satellite and two sub satellites.[67]

3.7 Aerial Missions

3.7.1 Mars

Relevant future missions: MSR Sample Retrieval Helicopter, future Mars aerial missions (e.g., Mars Science Helicopter)

In the past, orbiters have provided high-altitude aerial imagery of Mars, but with limited resolution. Rovers have provided rich and detailed imagery of the Martian surface, but move at a slow pace and are limited by terrain traversability and line-of-sight. In contrast to both orbiters and rovers, aerial vehicles can in principle traverse large distances quickly without being hindered by terrain, while providing detailed imagery of the surface from heights of a few meters to tens of meters above the surface (cf., Figure 9). Paired with a rover, a helicopter can act as a scouting platform, helping to identify promising science targets or mapping the terrain ahead of the rover. Looking further ahead, helicopters may one day carry their own science payloads to areas that are inaccessible to rovers.

Figure 9. Artist's rendering of a Mars Helicopter operating with the rover in the background. (credit: NASA).

Helicopter flight on Mars is enabled by an advanced onboard GN&C architecture that addresses the fundamental flight mechanics associated with achieving stable hover and forward flight in a thin planetary atmosphere, including a sufficient level of GN&C autonomy to perform end-to-end flights from take-off to landing reliably and without human intervention.[75] More details on GN&C for future helicopter missions can be found in Part IV of this report series.[4]

4 Onboard GN&C Technology Categories, Descriptions, and Status

Spacecraft onboard GN&C technology can be divided into four broad categories: 1) GN&C flight algorithms and software, 2) GN&C flight instruments, 3) other GN&C flight equipment, and 4) GN&C ground test facilities. Figure 10 shows the high-level interactions and dependencies between these various GN&C technology categories. Figure 11 shows a representative onboard GN&C Autonomy and Executive System that controls and coordinates the command and data flow between various elements of a complex GN&C system. The current section provides brief descriptions of these various technology areas.

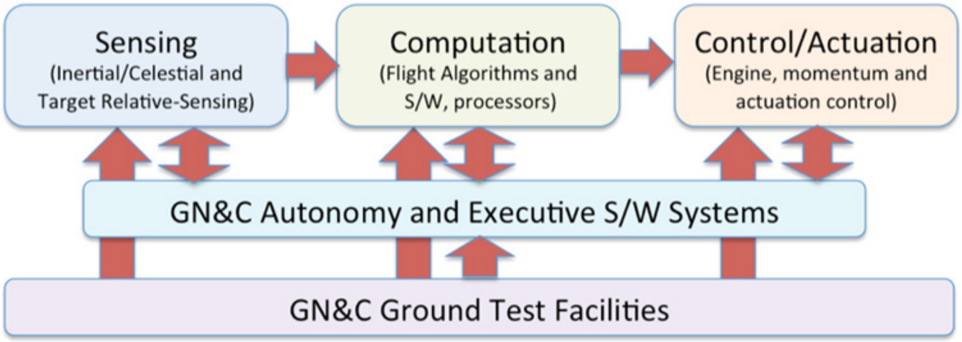

Figure 10. High-level interaction of GN&C technology categories. (credit: NASA/JPL-Caltech)

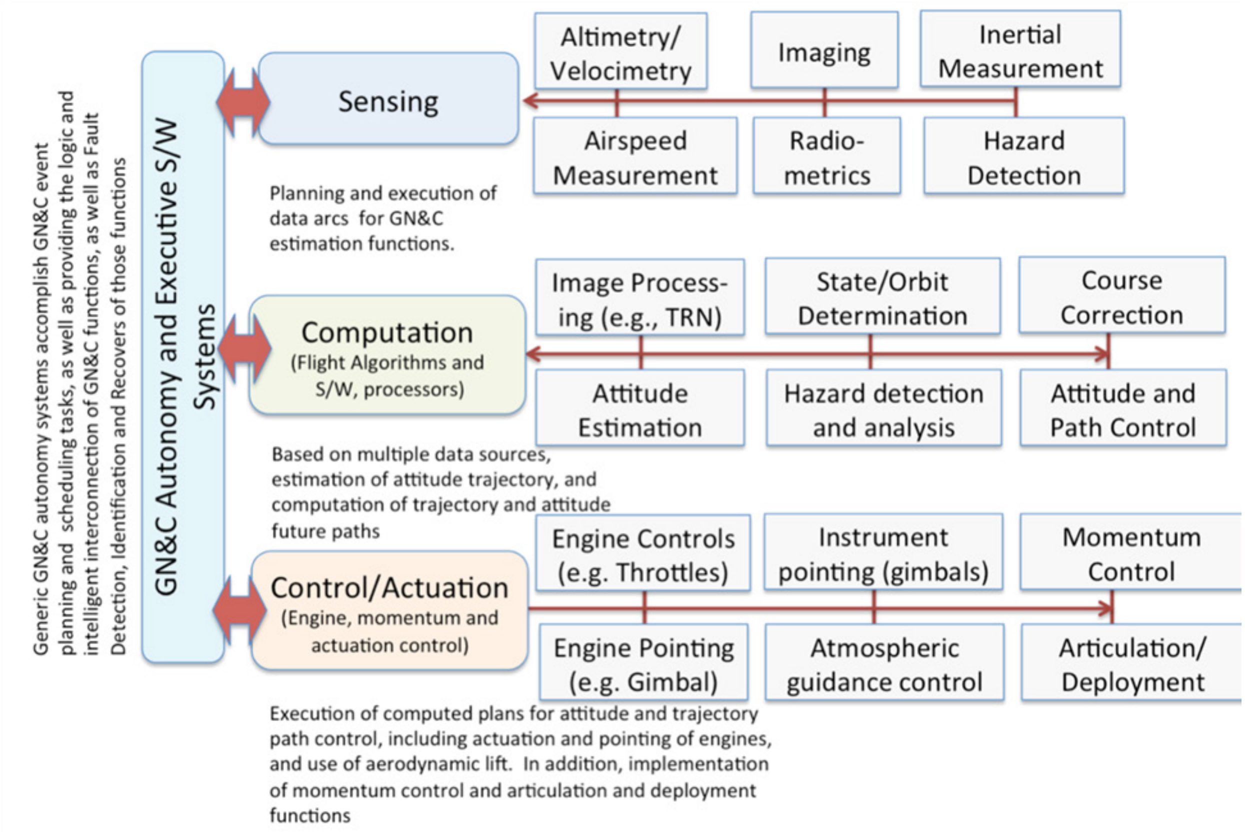

Figure 11. A representative Onboard GN&C Autonomy and Executive System that controls and coordinates the command and data flow between various elements of a complex GN&C system. (credit: NASA/JPL-Caltech)

4.1 GN&C Flight Algorithms and Software

4.1.1 Inertial Guidance, Navigation, Path-Planning, and Control

Onboard 6-Degrees of Freedom (DOF) G&C

Ideally, it is desired for onboard guidance algorithms to be computed in closed form without requiring iteration or human oversight. This way their behaviors could be fully understood, verified, and validated before being flown on a specified mission. Designing such algorithms is typically possible when the translational motions (3-DOF) and rotation motions (3-DOF) are effectively decoupled. However, more challenging onboard six degree-of-freedom (6-DOF) G&C algorithms need to be developed for autonomous applications where translational and rotational motions are more strongly coupled.[77–79] More strongly coupled dynamics requiring 6-DOF G&C often arise due to thruster configuration constraints, sensor field-of-view constraints, spacecraft-surface interaction constraints, and boundary conditions. For example, in the case of powered descent to the surface of a large body, (e.g., Moon or Mars), where the main descent thrusters are typically pointed along the axial direction of the spacecraft, the vehicle must first perform an attitude maneuver to point the thrusters properly to achieve the desired thrust force in the desired direction. Translational motion can also be coupled to rotational motion due to attitude constraints occurring during specific intervals of time, for example, to enable sensor target acquisition, pointing instruments to gather reconnaissance imagery, real-time feature tracking, or to satisfy boundary conditions or events. Another example is achieving a desired vertical attitude at touchdown so that the vehicle properly lands on its landing gear.

6-DOF G&C is also typically required when operating in close proximity to the surface of a small low-gravity body (e.g., asteroid or comet) to avoid undesired surface collision or contact. Moreover, if commanding a touch-and-go sampling event, there is typically a desired 6DOF guidance condition tied to the sampling event itself (e.g., best geometry supporting end effector). Afterwards, upon ascent from the surface, it is typically desired to hold a safe attitude in order to avoid surface recontact. Rendezvous and docking/capture applications also generally require 6-DOF guidance to ensure collision avoidance and to support docking and/or sample capture operations.

Status: The manned Apollo landings and the latest NASA Mars Entry, Descent, and Landing missions have successfully used onboard highly coupled 6-DOF G&C to land spacecraft.

Nonlinear Optimization and Path Planning

When a mission application has nonlinear state and control constraints, it is very difficult to find a guidance law that can be computed in closed-form and without requiring iteration. In this case, the guidance algorithm can most generally be posed as a numerical optimization problem subject to nonlinear constraints. This optimization approach poses a challenge for autonomous onboard applications because there is typically no formal proof or guarantee that an optimal solution can be found or that a reasonable upper bound exists on the computational time needed to obtain a viable solution. However, recent breakthroughs in convex optimization solvers based on interior-point methods have solved these challenges for several problems of practical interest and enabled onboard real-time guidance algorithms to become available for these applications.[80–82] Such algorithms have been able to expand the entire feasible flight envelope, while also ensuring optimality with respect to the chosen cost function. Using these type approaches, private companies have recently sent rockets into space and landed them safely back on Earth within meters of their targets.[83] At the core of these guidance laws can be found customized convex optimization flight code that guarantees a global optimal solution can be found in real time. Another important application of convex guidance is to the final powered descent stage of planetary entry. Here it can be used to determine a minimum-fuel trajectory to fly to the desired target landing point while also satisfying desired state and control constraints.[84,85]

Status: Guidance algorithms using convex optimization have been successfully implemented and flown for precision landing applications on Earth. Their extension to supporting future planetary exploration missions would help to minimize fuel and increase landing accuracy and would be an important technology development area over the next 10 years.

Autonomous GN&C Systems

The various elements of an onboard GN&C Autonomy and Executive System are shown in Figure 11. Principal among these are an executive control system and GN&C computational components, comprised of sensor data fusion and processing, state estimation, optimal attitude, translational, pointing guidance with hazard/body/object avoidance, ephemeris propagation, robust and high-performance attitude, translational, pointing control, actuator mixing logic, and functional and hardware fault monitoring and detection. These elements are retuned and reconfigured through changes in the executive system, which can be arranged for addressing multiple tasks across a wide range of mission scenarios. Part of the executive system responsibility will eventually need to extend to onboard mission planning, when changes in the environment, the status of onboard components, or the forecast trajectory requires changes in the mission plan. Onboard mission planning technology is discussed in Section 2 of Part I of this report series.[2]

***Status*:** The Deep Space 1 (DS1), Stardust, and Deep Impact (DI) missions flew an autonomous navigation system called "AutoNav," the operation of which was highly successful.[86] Autonomous navigation is discussed in Section 3.2 of Part I of this report series.[2] Autonomous navigation combined with onboard G&C functions have provided a completely autonomous GN&C computational capability (e.g., attitude estimation/control and trajectory control). However, it must be noted that these early missions flew onboard systems that were used for a single type of scenario—high-speed flybys. More recently developed advanced onboard GN&C capabilities were flown and demonstrated during the cruise phases of the Mars Exploration Rover, Curiosity, and Perseverance missions, which automated the generation of onboard delta-V maneuver sequences capable of handling both nominal and off-nominal flight scenarios. The associated advanced logic engine was also used in other mission-critical functions such as spacecraft turns and attitude knowledge acquisition prior to EDL. These types of advanced onboard GN&C functions could have a major impact in improving aerocapture performance at Venus, Uranus, and Neptune, since navigation and control updates could be made closer to the time of closest approach to the target body. EDL also benefitted from a number of GN&C autonomy innovations such as Curiosity's incorporation of Entry Guidance for landing-ellipse size reduction and Mars 2020 Perseverance's incorporation of Terrain Relative Navigation (TRN). This latter TRN function achieved a Mars landing that was close to the science target while also performing hazard avoidance (HA), i.e., by actively avoiding terrain hazards lying within the landing ellipse, making use of pre-flight-prepared hazard maps. Autonomous onboard GN&C functions were also developed for the Ingenuity Mars Helicopter and demonstrated on Mars, including altimeter-aided Visual Odometry for navigation[87] and solving the complex control and flight mechanics problem of flying a helicopter in a low-density atmosphere.[88] The main algorithm used for visual odometry, MAVeN, was developed originally for near-surface proximity operations in support of comet surface sample return.[89,90] A recent software upgrade to Ingenuity includes a simplified method for Hazard Detection and Avoidance (HDA) based on feature density[91], where hazards are assessed locally when hovering over the targeted landing site and avoided by a real-time computed final divert maneuver.

Considerable development beyond this state-of-the-art will be necessary to meet future mission needs. This includes an advanced onboard autonomous GN&C capability for improved EDL/DDL and Aerocapture performance at Venus, the Ice Giants, and outer planet moons; formation flying for lunar, asteroids/NEO exploration and planetary protection; GN&C for small body proximity operations; and ascent vehicle GN&C and rendezvous & docking to support sample return missions.

Integrated GN&C Software Systems and Multi-Source Data Fusion

With multiple mission scenarios comes the need for onboard GN&C to use and combine data from multiple sensors, including but not limited to imagers, IMUs, star-trackers, altimeters, velocimeters, and radiometric techniques. The data fusion mechanisms require complex and advanced filtering approaches that compare and contrast multiple data combination and weighting strategies to create an effective synthesis. Additionally, data editing and outlier rejection methods will be required to ensure against spurious and outlying data, which, in a mixed-data estimation, can cause serious divergence of solutions.

Status**:** Current G&C systems for 3-axis stabilized spacecraft typically fuse IMU and star-tracker data. AutoNav (previous section) has fused image data with accelerometer data to aid navigation during numerous small body encounters and fly-bys. Mars 2020 EDL carried the Lander Vision System (LVS) to fuse image data with Descent IMU data to significantly reduce position and velocity knowledge errors relative to prior art. The Ingenuity Mars Helicopter used the MAVeN filtering approach to fuse frame-to-frame image data with IMU data to reduce position error drift and support autonomous flight. Part IV of this report series contains more information on MAVeN for use in aerial navigation, including its history, sensor suite and performance characteristics.[4] Future systems will require the use of these data types and more, potentially including 3D lidar, autonomous sensors from the automotive industry being currently developed for self-driving cars, multi-spectral imaging, and radiometric updates with respect to Earth, orbiting spacecraft, or other assets.

Low-Thrust Guidance

Low-thrust high-specific impulse propulsion technologies, such as electrostatic, Hall-effect, or pulsed-plasma thrusters, are enabling and can increase science return for many proposed planetary exploration scenarios. These technologies provide an important option for all deep space missions including multi-target and sample return missions. Low-thrust guidance algorithms and technology are needed to support cruise thrusting in solar orbit to perform gravity assist targeting and to accomplish orbit capture, orbit transfer, and escape. New approaches are also needed to support small-body rendezvous, microgravity station-keeping, as well as proximity operations and landing. Translational guidance requires special low-thrust trajectory designs which are discussed in Section 2.6 of Part I this report series.[2]

Low thrust missions can benefit from an autonomous onboard guidance and control capability that can maximize the thrust level and thrusting duty cycle to preserve missed-thrust margin (i.e., margin to recover from events in which the spacecraft stops thrusting due to unforeseen problems). In addition, both Hall effect and electrostatic thrusters produce substantial “swirl” torques, which act to twist the spacecraft about its forward thrusting vector,[92] requiring more sophisticated control algorithms that closely integrate attitude control and delta-V guidance with onboard momentum management. Guidance architectures tolerant of uncertainties in EP thrust level, propellant consumption rates, solar array performance, gravity models, and gravity gradient torque are needed to maximize performance, as well as to simplify operations and improve mission robustness and flexibility. Moreover, many current Solar Electric Propulsion (SEP) architectures include flexible solar arrays mounted on single-axis gimbals, which need to be pointed to the Sun. The need to simultaneously point the thrust vector and solar arrays can create challenges for tracking rapidly changing desired thrust profiles (as required for missions with short-period small body orbits), without violating vehicle agility constraints.[93] As SEP spacecraft explore bodies further from the Sun (outer planets and their moons), the solar panels will by necessity become larger and more flexible. This suggests a need for new and tailored algorithms to perform agile pointing of thrusting vehicles with large flexible arrays in the presence of complex kinematic and dynamic constraints.

Status: DS1’s AutoNav demonstrated autonomous onboard correction of a low-thrust cruise trajectory. The Dawn mission used solar electric propulsion to perform a multi-body asteroid mission including orbit capture, transfer and escape. Hayabusa2 made use of electric propulsion to enable an asteroid sample return mission. The spacecraft used in the Psyche asteroid mission is a commercial satellite “all electric” spacecraft design using Hall-effect thrusters. Control algorithms developed for the Psyche mission make advances in the integration of thrust vector control with momentum management.

Solar-Sail Guidance and Control

Solar sails provide a potentially useful means of propulsion for future planetary spacecraft.[94,95] They use large thin sails to reflect sunlight, giving them a gentle push and almost unlimited fuel. Solar-sail trajectory designs share many characteristics with low-thrust electric propulsion but are far more restrictive. Special adaptations are necessary to the search and convergence tools to make onboard re-optimization of re-targeted solar sail trajectories tractable in an onboard environment. Solar sails are particularly well-suited to small, low-cost spacecraft, which can be limited by the lack of other propulsion options. Thanks to advances in technology miniaturization, smaller spacecraft have grown in capabilities, just as solar sails have advanced over the years. A promising planetary science application for their near-term use has been in the exploration of near-Earth objects (NEOs). Translational guidance is of the low-thrust type and requires special low-thrust trajectory designs as discussed in Section 2.6 of Part I this report series.[2] Onboard guidance and control challenges include attitude maneuvering with a flexible spacecraft, suppressing attitude errors induced by residual solar torques, and controlling with non-standard attitude actuators, for example, by commanding variable reflectance liquid crystal panels embedded in the sail. These complications make the guidance and control of a solar sail more challenging than with a SEP spacecraft. Unfortunately, these complications can become exacerbated in planetary scenarios like small body exploration and rendezvous applications. Here, 6DOF control and maneuvering of an extremely flexible solar sail in close proximity to asteroids or other bodies can be over-constrained and lead to full or partial collisions, or bodies becoming tangled in the sail. There is even a danger of being in the shadow of an asteroid, since control authority can be reduced or even lost completely due to lack of solar pressure.

Status: Guidance and control concepts for solar sail missions have been proposed in the literature over the last 10 to 20 years. The biggest solar sail actually built and flown to date is Japan’s IKAROS spacecraft developed by JAXA having a 196 square meter sail.[96] In 2010, the IKAROS mission successfully demonstrated early interplanetary guidance and navigation capability by changing its orbit around the Sun and successfully passing by Venus with the assist of solar radiation pressure. The Planetary Society’s LightSail 2 demonstrated flight by light in Earth orbit in 2019. To date, demonstrations have been mostly of interplanetary flight and to some extent flyby capability. However, as described above, additional onboard G&C technology development may be needed if solar sails are to be engaged in asteroid rendezvous and/or close proximity operations.

Distributed Spacecraft Cluster Control

Relative sensing, state estimation, and onboard autonomy are key considerations in most formation flying missions and especially for planetary science applications. In low-to-middle Earth orbit where, for example, an asteroid-hunting distributed aperture may be located, constraints are somewhat relaxed. Here, absolute and relative navigation capabilities (i.e., global navigation satellite systems, or GNSS) can be leveraged, and the formation can be monitored and controlled from the ground during acquisitions and in response to anomalies and off-nominal situations. For most planetary missions, however, no accurate absolute navigation source is available, making formation initialization and re-acquisition after a fault more challenging. Moreover, finding other spacecraft when outside of Earth orbit requires dedicated, wide-FOV inter-spacecraft sensing. Additionally, communication between planetary spacecraft and ground can be infrequent and delayed. As a result, more onboard autonomy is required, taking the form of sophisticated formation-level fault detection identification and recovery (FDIR), advanced collision avoidance algorithms, and more autonomous formation acquisition GN&C.

Once the formation has been acquired, LEO formation flying technology applies more readily to planetary conditions. For precision formation flying, generally centimeter-level position control and/or arc-minute-level relative attitude control or better, autonomous GN&C algorithms are needed to maneuver multiple spacecraft in proximity (1) safely: by avoiding collisions and light/plume contamination; (2) precisely: by meeting requirements for synthesizing an instrument aperture from multiple spacecraft and sensors; (3) reliably: by maintaining precision for many years and maintaining safety in fault conditions; and (4) efficiently: without requiring excessive fuel, computation, and/or communication as to make such missions infeasible.

GN&C algorithms for swarms are fundamentally different from those for precision formation flying.[97–99] This is due to the larger scale of the problem and the reduced capability of the individual swarm members. Probabilistic approaches in which high-level swarm behavior emerges from lower-level simple GN&C algorithms can achieve quite complex behaviors such as forming an aperture and autonomous self-repair.[100,101] Some initiatives such as the Silicon Wafer Integrated Femto-satellites (SWIFT) aim to demonstrate swarm technology in Earth orbit. Significant advances in the fields of artificial intelligence and machine learning (AI/ML) may also play an important role in the continued maturation of swarm technologies over the next decade.

***Status**:* No major individual technological barriers stand in the way of formation flying in Earth orbit, and, in fact, several two-spacecraft LEO formations have already flown. However, the extension of formation flying to planetary missions in deep space will be complicated by the inability to leverage GNSS or rely on regular communications with ground. Further challenges may arise if spacecraft in a formation must point to one another from large distances, requiring precision pointing capability. For example, in a radio occultation type mission such as VASCO,[102] if there is no direct line-of-sight to Earth then individual spacecraft must accurately point to each other across long baselines due to being in different locations in a Venus orbit. For even more ambitious planetary missions involving more than two spacecraft and/or requiring complex maneuvers, it is expected that formation-level TRL6 demonstrations of autonomy, robustness, and performance will be needed, and potentially even a dedicated flight demonstration, before formation flying can be suitably recognized as a viable flight-qualified technology.

Precision-Pointing systems for Planetary Missions

Future planetary missions will require precision pointing of uplink and downlink laser beacons from/to Earth and from/to assets on the planets being explored. This capability is needed for optical communication terminals that can enable 10 to 100 times higher telecom rates when compared to typical RF radio antennas. As the distance from Earth to the explored planet increases, the required pointing performance tightens and so does the need for more accurate navigation. This in turn points to the need for improved or new onboard accurate navigation (for optical communication). Imaging campaigns at distant planets could also benefit from precision pointing GNC architectures that decouple the operations of multiple instruments and allow simpler and more autonomous operations. Such decoupling can come in the form of passive or active isolation of articulated instruments like the NAC and MISE instruments on the Europa Clipper spacecraft. Such distributed solutions are not currently used routinely, and could benefit from further development.

***Status*:** OPALS, the first demonstration of an optical communications link from space to Earth has been flown on board the International Space Station and has shown successfully (March 2015) that adaptive optics on the ground can decode video content included in a downlink beacon from space. The Deep Space Optical Communications (DSOC) payload on the Psyche mission brought GN&C challenges and advances in magnetic isolation/suspension and optical tracking for very high-performance pointing applications. The DSOC terminal is planning to demonstrate the capability to sustain up-link and down-link communications between Psyche and Earth over a distance of nearly 3 AU.[103] GN&C developments for both the Europa Clipper and Psyche missions had to deal with attitude control and pointing problems caused by extremely large and flexible solar arrays, in addition to the vibration problems caused by disturbances, such as those from reaction wheels, and their effects on the pointing stability of their high precision planetary science instruments. The challenge for optical communications beyond Saturn becomes significant since using an uplink beam would no longer be feasible. Specifically, the beam energy has to be so large that it exceeds environmental constraints and may also induce refractive index changes in the atmospheric column on Earth that significantly distorts the beam. It is expected that alternative pointing architectures and methods would be needed for downlink tracking to Earth in this case.

Aeroguidance and Control

Guidance and control laws for atmospheric entry are varied, and in general, specific mission scenarios will require custom development. However, the underlying framework of the onboard real-time, closed-loop GN&C control system will be in common to all scenarios and includes such elements as IMU data filtering, attitude and position propagation, and executive control. The development of product lines of aeroguidance subsystems that exploit these commonalities will enhance the economics of future missions that require aeroguidance and control for atmospheric entry.

Status: Mars Science Laboratory (MSL) and Mars 2020 have used the same approach for entry of the aeroshell as used by the Apollo capsules, namely reorienting the lift vector by controlling the vehicle bank angle. Cross-range motions induced by resulting horizontal components of lift are then mitigated by periodic bank reversals. Many other techniques for aeroguidance and control are possible, including attack-angle adjustment of a lifting body, drag/lift-tabs, other drag/lift control, with many variations. All of these new alternatives are at relatively low TRL but can lead to higher controllability for improved fuel savings and terminal accuracy. It is worth noting that many of these aeroguidance and control alternatives already have terrestrial analogs, although not currently at the supersonic velocities required for atmospheric entry.

4.1.2 Target-Relative Estimation

Target-Relative Navigation and Visual Odometry

Terrain Relative Navigation (TRN) provides a map-relative and therefore absolute position fix that can be used to accurately target specific points on planetary surfaces.[104,105] There are multiple different approaches to TRN, but they all match sensor data collected on board to a map generated a priori. Typically, due to their high angular resolution, visible cameras and lidars are used for the onboard sensor measurements. Image correlation or image signature matching are often used to match landmarks for camera-based approaches while lidar-based approaches correlate elevation contours or patches.[106,107] These matches can be used to estimate a kinematic position (and optionally attitude) or are fed into an estimation filter to be combined with other sensor measurements to determine the full spacecraft state at high rate. For lidar approaches, digital elevation maps are used for the a priori map, while camera approaches also require the map to have a layer that describes the visual appearance of the scene.[107] This can be actual orbital images or rendered elevation maps.

An alternative to TRN is Visual Odometry (VO), or Visual Inertial Odometry (VIO) if camera-based solutions are blended with an IMU. VO matches features between consecutive time samples of onboard image data to provide an estimate of target relative motion.[108] In camera and lidar-based approaches to VO, local patches of data are typically matched through correlation. For camera-based approaches, an independent method for determining distance to the surface is generally required to provide scene scale so a full change in position can be estimated. VO can be used in a closed loop GN&C system for velocity estimation and station keeping. VO measurements can also be integrated over time to provide a position estimate relative to the starting sample of the onboard data. The main advantage of VO compared to TRN is that the vehicle can traverse completely unknown terrain without requiring any prior map or associated landmark catalog. The main disadvantages derive from the fact that position is obtained essentially by integrating noisy velocity measurements, so they tend to drift with time and are defined relative to the starting point instead of being tied to an absolute coordinate system.

Status**:** Significant advances have been made for TRN and VO in the last decade. The OSIRIS-REx mission used a TRN approach called Natural Feature Tracking to enable touch-and-go sampling at the surprisingly hazardous asteroid Bennu[109] (cf., Figure 12). The Mars 2020 mission developed the Lander Vision System (LVS) so that it could use onboard map-relative position estimation to target a safe-landing location in the very hazardous Jezero Crater landing site[110] (cf., Figure 13). The Mars helicopter Ingenuity uses VO to estimate position relative to the takeoff location so that it can fly along a trajectory,[111] and the Dragonfly octocopter mission to Titan will use VO in a similar fashion[112] but will also benefit from lower drift IMUs possible in a much larger vehicle and required for longer flight times. Advances are still needed. Crewed missions to the lunar south pole may need an active lidar-based approach to land in permanently lit regions. Such permanently lit regions only occur at the south pole where the illumination in the approach to the landing site can have many large shadows or no illumination at all until the very end of the trajectory. Ideally, it is desired to develop a bolt-on type of TRN sensor system that is “fully

Figure 12. Illustration of OSIRIS REx approaching the asteroid Bennu. (credit: NASA)

autonomous" in the sense that it produces position/pose estimates without any input from the host spacecraft. For example, such a sensor system would not require the host spacecraft to provide accurate position and velocity information for initialization purposes or share computational resources or require accurate and continuous attitude knowledge from the host spacecraft. This would simplify spacecraft design and could greatly expand the range of missions that utilize TRN. Active areas of research include the development of long range lidars, landmark matching techniques that are insensitive to illumination changes, and cross modality feature matching (e.g., visible to SAR).

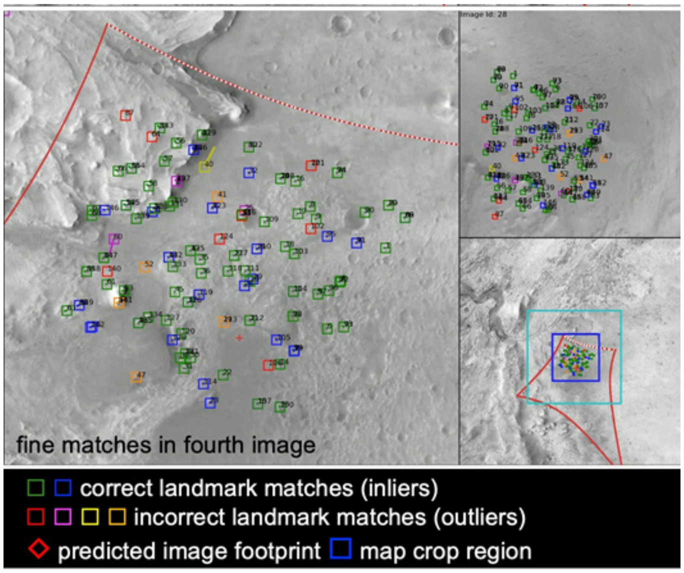

Figure 13. Landmark matches from Mars 2020 EDL. (credit: NASA/JPL-Caltech)

Hazard Detection and Avoidance

Hazard Detection and Avoidance (HDA) is a landing function that uses data collected on board to detect safe landing sites in real time as the vehicle descends.[113] After detection, the vehicle is diverted to the autonomously selected landing site. It is useful to distinguish HDA from Hazard Avoidance (HA). In HA, hazards do not have to be recognized in real time, but rather, the onboard system can make use of pre-flight-prepared hazard maps. The ideal sensor for HDA is an imaging lidar that can quickly generate a high-resolution elevation map over an area many times the size of the lander. Camera images can also be used for HDA but the hazards need to be inferred from two-dimensional visual clues and information rather than directly measured heights, for example, through the length of cast shadows or the brightness variation in a local region. This is problematic at Titan where the dense atmosphere leads to diffuse lighting and no sharp shadows.

A special case of HDA is Hazard-Relative Navigation (HRN). HRN is designed to address the common case, such as for Lunar landing, where prior information is good enough to get you in the vicinity of a landing region but is not good enough to provide detailed information about local hazards in that region. In addition, landmark catalogs prepared using orbital assets that were reliable at high altitudes typically become less reliable as one descends to lower altitudes. HRN addresses both of these problems. HRN requires an onboard capability to generate a sequence of 3D digital elevation maps (DEMs) on the fly as the vehicle descends. This generally requires carrying additional sensors such 3D lidar or stereo cameras that are turned on when the vehicle is in the vicinity of its landing region. The main idea of HRN is to use the same DEMs for both navigation and hazard detection. An example of HRN applied to Lunar landing is the ALHAT Hazard Detection System (HDS).[114] ALHAT HDS uses a flash 3D lidar to create the DEMs. The very first DEM is used as a reference for the remaining navigation updates. Subsequent DEMs from the flash lidar are then correlated to the original DEM to calculate offsets that are provided to the navigation filter. The specific purpose of HRN is to minimize the growth of navigation position errors during descent so that even the smallest possible safe haven can be reliably targeted.

HDA will be needed for the Dragonfly rotorcraft mission to Titan. Since radar images for Titan have lower resolution than images for Mars, the vehicle will need to carry its own lidar for hazard avoidance purposes. The Dragonfly landing and hazard avoidance strategy is discussed in more detail in Section 5.2.4 of Part IV of this report series.[4]

Status**:** The Chinese Space Agency has successfully employed HDA during lunar[115] and Mars[116] landing, albeit by hovering the spacecraft and using a fairly slow scanning lidar. NASA has not used HDA on a flight mission yet, but numerous relevant technology programs are currently in existence or have already been completed. For example, the ALHAT/Morpheus technology program successfully demonstrated HDA and HRN on a vertical take-off and landing rocket (cf., Figure 14).[117] Higher rate and longer range lidars that can map a 100x100 m area in a single-second are in development in the SPLICE and Europa Lander technology programs.[118,119] The Dragonfly mission to Titan plans to use a lidar for HDA, and missions to Europa, Enceladus, and the moon could also benefit from this technology.

Figure 14. Morpheus demonstration of onboard hazard detection and avoidance showing the terminal portion where the ALHAT onboard Hazard Detection System (HDS) identifies a safe landing site 1.4m east of the pad center and diverts to land at that location. (credit: https://youtu.be/tmkPJUHYdRA)

4.1.3 Helicopter / Rotorcraft Control

Designing an onboard GNC system for a helicopter is a challenging task in general, due to various unusual characteristics of helicopters as compared to other vehicles.[120–123] In particular, helicopters are typically unstable in open loop, exhibit significant coupling between different vehicle axes, and are subject to high levels of vibration. The control design problem becomes more challenging when, as in the case of the Mars Helicopter, the vehicle must take off and land on unprepared terrain and navigate without external aids such as GPS. Most challenging of all, however, are those aspects that are unique to flying on Mars: (1) the atmospheric density is very thin and only about 1% that of Earth, and the gravity is only about 38% that of Earth; (2) little prior information exists on how these differences affect the flight dynamics in the Martian environment; (3) the Mars environment cannot be fully replicated when testing on Earth; (4) the helicopter control system must work the very first time it operates in its intended environment.

The development of an onboard GNC system for a Mars helicopter calls for detailed modeling, analysis, and simulation, combined with testing in partially replicated environments. Simple analytical models combined with scaling arguments are helpful in the beginning to understand the fundamental differences between Earth and Mars helicopter flight and for developing the intuition necessary for generating a coherent GNC architecture. High-fidelity modeling combines multi-body dynamics and aerodynamic modeling, which guides both the design of the vehicle and the control algorithms. Finally, system identification experiments are generally required to be carried out in various test configurations inside a vacuum chamber at Mars density in order to determine key properties of the actual helicopter dynamics.

An important option for Mars Helicopters is to perform deployment in midair, rather than requiring the more expensive option of landing a special deployment platform and then deploying the Helicopter from the platform. This is sometimes denoted as entry/descent/deploy (EDD), which provides an important alternative to landing for airships. In EDD, all of the overheads of mass and cost for landing a separate exploration vehicle are avoided. These aerial deployments would require verifiable and validate-able concepts of operations equal to a hybrid of what was done for Mars 2020 EDL and Ingenuity combined. This approach could lead to a new class of science-capable and affordable aerial roving missions on the surface of Mars, allowing more capable delivery of small science payloads to multiple locations, at higher elevations, and over more rugged terrain than previously thought possible. It is worth noting that a similar mid-air deployment concept is currently being used for the New Frontier's Dragonfly mission during descent into the thick atmosphere of Saturn's moon Titan.

Status: The Ingenuity Mars Helicopter flew as a technology demonstration on the Mars 2020 mission that was carried and deployed from the Perseverance Rover. Ingenuity demonstrated the capability for stable flight in the Martian atmosphere, including take-off, forward flight, hover, and landing. All operations were based on having a sufficient level of onboard GNC autonomy to reliably execute pre-designated flight plans without human intervention. After completing its technology demonstration, Ingenuity was re-introduced into the M2020 mission with a new operational role to perform an official scouting function for the Perseverance Rover.

For future missions, it is desired for Mars Helicopters to be larger and more capable, with the ability to perform more advanced scouting functions, carry large and complex instruments, and autonomously perform sampling in support of data collection and/or in-situ science. The pathway to such larger Mars Science Helicopters is described in more detail in Part IV of this report series.[4] Recently, a new role has been defined for two upgraded Ingenuity-type Mars Helicopters to be part of the upcoming Mars Sample Return (MSR) mission. Specifically, they have been baselined to deploy from the back of the MSR lander to support sample retrieval activities on Mars. For this purpose, they will be outfitted with wheels to traverse terrain, an arm for retrieving samples, and given more control authority to carry heavier payloads. Such modifications are a step in the right direction toward achieving more capable Mars Science Helicopters for future exploration.

4.1.4 Aerocapture and Control

For planets with atmospheres, aerocapture is an orbital transfer maneuver in which a spacecraft uses the aerodynamic drag force from a single pass through a planetary atmosphere to reduce its velocity to achieve insertion into orbit.[124–130] Methods for aeroguidance and control can also be applied to the aerocapture problem if the terminal guidance condition is changed from a decelerator deployment condition (LDSD, ballute, parachute, etc.) to instead ensuring that a proper terminal delta-V has been achieved. Here, the controlled path is actively adjusted through the atmosphere to ensure that the accumulated atmospheric drag achieves the desired delta-V, which in turn, ensures that the spacecraft is captured from its initial hyperbolic approach trajectory into a targeted final closed orbit. This all takes place in a single pass so that aerocapture, similar to EDL/DDL, is a one-shot critical event. The achieved orbit can be further lowered in a fuel-efficient manner by using aerobraking, which reduces the apoapsis of a spacecraft over consecutive passes, again by using the planet's atmosphere to slow the vehicle. Missions benefitting from aerocapture and aerobraking include any scenarios where the required fuel mass would be prohibitive using a standard propellant burn for capture, for example, for achieving short trip times in large orbiter missions to Uranus or Neptune or small satellite orbit insertion at Venus, Mars, or Titan. Acceptable fuel mass for these missions can often be achieved if one is prepared to tolerate very long trip times. However, traveling with higher velocities to shorten the trip time, in turn, requires more fuel to insert into orbit upon arrival. Fuel penalties to shorten trip times quickly become prohibitive, which is where aerocapture becomes a powerful alternative. For any planetary body in the solar system other than Mars or Earth, targeting can be significantly degraded by lack of precise knowledge about the location of the planet. Additionally, for the Gas Giants, knowledge and model uncertainty of the atmosphere are also strong drivers affecting targeting accuracy and performance.

Traditional orbiter spacecraft bus architectures must now also include an aeroshell, minimally with a heat shield forebody and potentially an aft-body enclosure if the aerothermal environment and spacecraft design specifics require it. GN&C and Systems Engineers must work closely to justify the application of aerocapture. At a minimum, the mass of the aerodynamic deceleration, aerothermal protection, separations mechanisms, and fuel required for RCS steering must be compared to the fuel and propulsion system for an all-fuel orbit insertion burn design (current state of the art) and shown to provide significant benefit, adding more payload (science) capability to the mission as a result. Other design trades must be performed, like delta-V-for-mass efficiency for types of drag devices, complexity and mass efficiency of separation mechanisms/dynamics, and extensive uncertainty quantification of aerocapture design elements to both spacecraft navigation knowledge error uncertainty/variability at delivery conditions and variability/uncertainty in the atmospheric profile knowledge. The cruise configuration of the spacecraft must also be considered in such design trades including thruster placement and the placement/orientation of solar panels, communication antennas, and other appendages. All of these results will be closely tied to the Mission Design and Concept of Operations for any given mission and will drive selection of the desired technologies and algorithms.

With regard to planetary missions, aerocapture technology offers the possibility to significantly increase the delivered mass and reduce time of flight (TOF) in support of NASA's exploration of Uranus and Neptune.[124] This is particularly relevant to the current Decadal Study's highest priority for a Uranus Orbiter and Probe Flagship mission. Studies have shown that to accommodate the large uncertainties associated with aerocapture at Uranus and Neptune, aerocapture vehicles must have a sufficiently large L/D (lift-to-drag ratio) between 0.6 to 0.8.[125] This is in contrast to vehicles that have been used for all interplanetary entry missions flown to date, which are either ballistic (L/D=0) or low-L/D vehicles (L/D ≤ 0.4). Unfortunately, designing, developing, and testing such a new mid-L/D vehicle will require a substantial funding commitment and at least a decade of time. As an alternate approach, certain GN&C technologies can be advanced to enable the use of standard low L/D vehicles. Specifically, this can be done by focusing on mitigating the two main sources of aerocapture performance degradation: (1) navigated delivery errors at the atmospheric interface and (2) uncertainty/variability in the planetary atmosphere. Additional discussion of autonomous navigation can be found in Section 3.2 of Part I this report series.[2]

Concerning (1): Improved navigation can be realized by combining radiometric tracking with optical navigation, assuming available target body ephemeris accuracy is sufficient to provide the necessary optical navigation accuracy and that the last optical measurement is taken sufficiently close in time to the atmospheric entry point.[126] It is worth noting that making this last measurement too close to entry (shorter than a few days) could drive the need for an autonomous onboard capability that is able to process late-breaking navigation updates completely without the benefit of ground intervention. Concerning (2): Onboard methods can be developed to learn appropriate atmospheric density models or to make real-time density measurements that are used to update the guidance law to help desensitize it to atmospheric uncertainties.[127] Recent studies incorporating the above types of GN&C improvements have shown encouraging results and support the possibility for using lower L/D vehicles (0.3-0.4) to achieve aerocapture at the Ice Giants.[128–130] Additional concepts to potentially reduce required vehicle L/D are also discussed in Girija 2020.[128]

Status: Concepts in the literature include using the Apollo entry guidance or predictor/corrector guidance laws with a steerable lift vector or trim tab to fly through the atmosphere. Here the vehicle dips deeper into the atmosphere to get more drag or pulls into a shallower trajectory to reduce drag, in a controlled fashion, in order to hit the desired terminal delta-V condition. This heritage was largely leveraged for aeroguidance and control in the Mars Science Laboratory and Mars 2020 missions. Detachable drag skirts have also been studied and seem to be feasible using inertial sensor packages to measure and integrate the delta-velocity provided by drag. These drag skirts could be rigid or deployable, using current Hypersonic Inflatable Aerodynamic Decelerator (HIAD) and Adaptive Deployable Entry system Project (ADEPT) concepts, provided that the separation mechanism designs and associated dynamics are feasible to minimize complexity of the separation event (e.g., no re-contact, small aero disturbances, etc.). From a GN&C perspective, the guidance laws that achieve vertical profile steering for delta-V accumulation should be as deterministic and repeatable as possible in terms of computational needs to make vehicle/system-level V&V less onerous by reduction of the required algorithm/timing test space.

It is important to further develop those areas of GN&C technology that enable the effective use of high-heritage standard low L/D vehicles for aerocapture at the Ice Giants. This includes methods that can reduce the navigated delivery errors at atmospheric entry and onboard methods that can learn/adapt the vehicle guidance laws to modeling/dynamics uncertainty and variability in the planetary atmosphere.

4.1.5 Small Satellite Precision Pointing

The number of small satellites that have been launched has increased dramatically over the past 10 years. The investment in this area has significantly increased the capability of these spacecraft, including precision pointing. For future planetary science missions, precision pointing applications include deep-space optical communication and stable pointing for scientific targets of interest. For optical communication, the onboard GN&C will be required to be able to acquire and track its target and point its downlink beam with a point-ahead angle computed using onboard knowledge. Future science missions may require autonomous selection and tracking of scientifically interesting features, which will need to be fed directly into the control system to provide target-relative stable instrument pointing. The main challenge for small satellites is the ability to find small mass, volume, and power sensors and actuators and the associated algorithms to use with this hardware to meet stringent pointing requirements.

Status: The Miniature X-ray Solar Spectrometer (MinXSS) has demonstrated a pointing stability of 30 arcseconds (3σ) over 10 seconds using reaction wheels and a star tracker.[131] Using a two-stage pointing control system and payload feedback, the Arcsecond Space Telescope Enabling Research in Astrophysics (ASTERIA) demonstrated a pointing stability of 0.5 arcseconds (RMS) over 20 min[132] (cf., Figure 15). As the capability of small satellites continues to improve, fueled by continuing miniaturization of sensors and actuators, future planetary science missions will rely more heavily on precision pointing, and opportunities for leveraging available payload precision sensing to support the pointing control system.

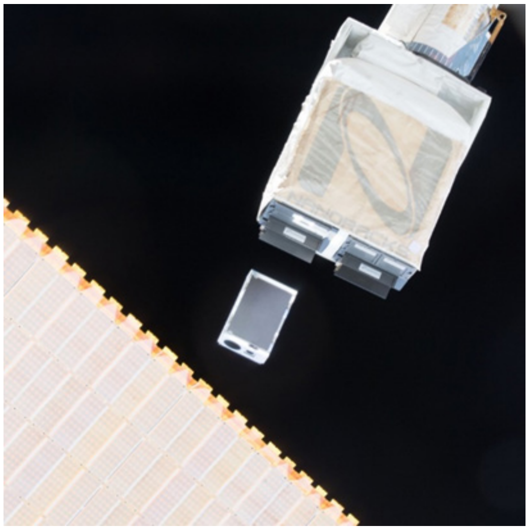

Figure 15. Deployment of the Arcsecond Space Telescope Enabling Research in Astrophysics (ASTERIA) CubeSat from the International Space Station (ISS) which achieved a pointing stability of 0.5 arcseconds (RMS) over 20 min.[132]

4.2 GN&C Flight Instruments

4.2.1 Target-Relative Sensing

Altimetry and Velocimetry

Lidar and radar are obvious sensor technologies for altimetry, time-of-flight ranging, and velocimetry (e.g., Doppler measurements). However, they are not the only choices. Passive and/or active imaging based on using visual odometry (frame-to-frame picture analysis), or structured light (illumination of the surface with known angular patterns) provide two alternative methods for altimetry and velocimetry, especially when operating close to the surface or target. Non-stereo passive imaging supported by TRN image processing can also provide altimetry and velocimetry when processed through an autonomous navigation filter that accurately models the spacecraft dynamics or when aided by precision accelerometers for trajectory propagation.

***Status*:** This field has seen significant development in the last 10 years. Laser range finders have recently been flown on the Mars Ingenuity helicopter and have been used for docking on the International Space Station. Another example is the M2020 mission, which used a radar for velocimeter and altimetry. Currently, the agency is making a large investment in long-range lidars (many kilometers), as relevant to a future Europa Lander mission. Also, lidar-based landing sensors are being considered for the Human Landing System (HLS) and for space station docking. The ALHAT and Autonomous Ascent and Descent Powered-Flight Testbed (ADAPT) projects explored TRN technologies. A lidar-based altimeter has also been baselined for providing slant range measurements during EDL for the upcoming Mars Sample Return Lander.

Terrain Sensors

Terrain sensors can be simple visible or IR imagers that have no range limitation but may require ambient illumination or active sensors that have range limitations that can operate independently from ambient illumination. In many cases, terrain imagers can be the same instruments as the science imagers; in general, however, GN&C does not need color imagery.

Status: Cameras have been flying essentially as long as spacecraft have, and virtually any camera can serve as a terrain sensor. However, for navigation purposes, there are frequently many regimes of operation, often requiring large dynamic range and enhanced sensitivity to sense dim signals without undue image smearing. Many missions have incorporated high-precision instruments that have successfully combined science and navigation capabilities, including the two Voyagers, Cassini, DS1, DI, Messenger, and ESA's Smart 1. Today, CMOS-based focal planes are more common than CCD based focal planes. Lidars generating a 3D representation of the surface are also expected to play a role in the future. This includes terrain profile acquisitions at high altitudes to enable vehicle localization with respect to a terrain reference frame in unlit or poorly-lit conditions such as permanently shadowed regions on Moon.

Hazard-Detection Sensor

Flash and scanning lidars are preferred sensors for hazard detection because they provide nearly instantaneous maps of the surface relative to the spacecraft. This gives a direct method to recognize and assess hazards rapidly. Although at shallow look angles hazards can be difficult to interpret, they can still be assessed sufficiently to provide a basis for a terminal descent trajectory.

***Status*:** While NASA has not flown any dedicated hazard-detection sensors to date it is planning to do so on the Dragonfly mission. Moreover, numerous relevant technology programs are currently in existence or have already been completed. As an enabling technology for mission concepts like Europa Lander, two next generation lidars are currently under development. One lidar is from industry vendor Hexagon US Federal,[133] and the other is from MIT Lincoln Labs.[134] Both are based on photon-efficient techniques while being robust to extreme radiation. Moreover, their design flexibility allows for operation on multiple airless and atmospheric bodies such as Moon, Mars, Enceladus, Titan, and other small bodies (comets, asteroids). The lidars are projected to be TRL5-6 at the conclusion of the helicopter field tests in 2022/23.

Inter-Spacecraft Sensors

Typical formation-flying architectures rely on a series of handovers between sensors with increasingly narrow fields-of-view and increasingly fine accuracy to acquire and maintain formations. For instance, radio-frequency (RF) and/or vision-based sensors with wide fields of view can provide initial meter-level or centimeter-level relative sensing for acquisition, which can handover to certain infrared or optical links capable of providing down to millimeter-level accuracy. The ability to perform these handovers autonomously has been demonstrated by several Earth-based missions (e.g., Orbital Express,[135] the Automated Transfer Vehicle,[136] or the Prototype Research Instruments and Space Mission Technology Advancement [PRISMA][137,138]). However, a significant advantage for formations and swarms in low-to-middle Earth orbit is their ability to leverage GNSS; in contrast, deep space and planetary-orbit missions must rely on direct inter-spacecraft sensors.

Beyond two-spacecraft formations, locating others, identifying them, and maintaining several communication and relative sensing links simultaneously requires complex maneuvering or alternatively, an omnidirectional-sensing and communication capability. In addition, interference can become an issue with several RF cross-links, while vision-based sensors are likely to encounter several glinting spacecraft and possibly large bright objects (e.g., a planet) in a given image. Although some designs are being developed (e.g., the Inter-Satellite Omnidirectional optical Communicator [ISOC],[139] Starshade,[140] and others[141,142]), more work is needed to mature high-precision omni-directional sensors and communication links capable of tracking several spacecraft at the same time.

Status: Lack of GNSS makes formation flying more challenging outside Earth orbit. Various mature inter-spacecraft sensor technologies currently exist for two-spacecraft formations. For larger formations, high-TRL high-accuracy omnidirectional relative sensors capable of tracking several spacecraft simultaneously are needed.

Atmospheric-Relative Sensing

Measurement of the relative airspeed of a vehicle entering the atmosphere may lead to increased performance of the GN&C system, especially through improvements in the onboard G&C estimation algorithms. A great deal of uncertainty exists in the scale heights of planetary atmospheres, and such poor atmospheric knowledge can map into large terminal trajectory errors. By measuring the air-speed profile and density, adjustments can be made to the trajectory in flight to improve terminal accuracy.

Status**:** In principle, atmospheric-relative rates can be measured for improving the guidance accuracy through planetary atmospheres. In practice this can be done using supersonic Pitot tubes sensors. Unfortunately, such devices are currently at a very low TRL for space applications. Developing supersonic Pitot tube technology to a higher TRL level is a promising area for improving terminal guidance performance. Likewise, developing alternative methods for atmospheric-relative sensing would also be valuable. It has been hypothesized that atmospheric optical transmission can also be used to measure atmospheric density.

4.2.2 Inertial/Celestial Sensing

Nano-g Accelerometers and Precision Gyros

An inertial measurement unit (IMU) is an important sensor consisting of a 3-axis gyro and 3-axis accelerometer. The IMU plays an important role in many missions because, in the absence of navigation updates or external observations, a vehicle can continue to propagate its position and velocity by integrating the onboard IMU. However, IMUs are never perfect and their internal biases and drifts cause position and velocity errors to increase with time. In practical applications, these IMU drifts fundamentally limit the amount of time that a vehicle can go without having suitable navigation updates. In fact, many GN&C mission scenarios are dominated by IMU errors. Examples include exploration vehicles that must travel through thick opaque atmospheres (e.g., Venus balloons, and long-duration parachute descent on Titan), melt through thick ice layers (e.g., Europa cryobots), or travel under water (e.g., Europa submarines). IMUs are especially important in the atmospheric entry phase of EDL where there is a critical blackout period during which TRN data cannot be obtained.

There is a common misconception that position and velocity errors accumulated during IMU propagation are due primarily to errors in the accelerometer. This is not strictly true. Accelerometer measurements are observed in the body frame but are only meaningful if propagated in the inertial frame. Since accurate attitude information is needed to transform between body and inertial coordinates, the quality of the gyro also contributes heavily to the position and velocity propagation errors. Hence, when improving an IMU to be used for inertial propagation applications, improvements in accelerometer technology must be matched by commensurate improvements in gyro technology.

Status**:** Accurate accelerometers exist as science instruments (on e.g., GRACE-FO, and Mars Insight).[143] However, current GNC space accelerometer technology is less accurate. We believe science-instrument level performance for space inertial instrumentation could be brought to flight readiness in fairly short order. As an example, a high-precision optical interferometry-based accelerometer assembly is currently under development via collaborative efforts between JPL and Texas A&M University, with a targeted performance level of 1e-10 g over 1000 seconds.

Low Mass Inertial Measurement Unit (IMU)

New mobility-type missions are beginning to emerge that include Mars helicopters and future Venus balloons. In considering IMUs for these types of missions, it quickly becomes clear that a conventional, redundant set of space-qualified fiber-optical gyros will have too much mass and/or consume too much power. By necessity, these types of missions will need to consider using MEMS based IMUs to reduce mass and power. Unfortunately, there are currently no MEMS IMUs that are space qualified for Class B missions or higher.

Status: A commercial off-the-shelf (COTS) MEMS IMU was already flown on a NASA Class D experiment as part of the Mars Ingenuity helicopter demonstration. The Ingenuity gyros were measured on Mars to have a drift rate of 3 deg/min.[144] This compares to 1 deg/hour for a typical higher-SWaP space-qualified tactical grade gyro, and 0.02 deg/hour for a precision gyro of the type often used for EDL. Other examples exist where MEMS based IMUs are being used for launch vehicles and micro-satellites. It is recommended to space qualify MEMS-based IMUs for use in future NASA Class B missions.

Precision Time Determination

A number of important mission scenarios and GN&C operations are degraded by spacecraft clock drift. These include spacecraft-to-spacecraft navigation using one-way radiometric measurements and precision in-orbit surface mapping. In the first case, the interpretation of the one-way signal—especially the ranging signal—is dependent upon having coordinated time synchronization. In the case of orbital mapping, time error causes the misinterpretation of the onboard navigation ephemeris, which causes errors in placing the desired remote-sensing footprint on the surface of the target body. By placing clock references on the spacecraft that have a quality on the order of the best Earth ground-station clocks, these problems vanish. High-precision space clocks also enable a potentially important application, namely the positioning of one-way radio beacons on asteroids that represent possible Earth-impact risks. One-way radio links greatly reduce the size and mass of the beacon package, and may allow for many such beacons to be planted in the future, thus providing a permanent means of keeping watch on solar system threats of particular concern.

Status: The Deep Space Atomic Clock (DSAC) has been developed as an advanced prototype atomic clock for future deep space navigation and radio science and DSAC2 was scheduled to fly on Veritas prior to funding cuts. DSAC and its application to precision one-way radiometric tracking is discussed in Section 3.1.1 of Part I of this report series.[2]

Milli-Arcsecond Pointing

Though principally required for observatory pointing systems, milli-arcsecond pointing control will also be required for optical communications, which is a long-term enabling capability for future planetary missions. Instrumentation and controllers for both sensing and actuating the perturbations and corrections for such tight pointing are important GN&C elements not only for observatories and optical communications but for very-high-resolution imagers that might be deployed in planetary systems in the future. Hardware to support precision-pointing technology includes a wide range of precision optical-metrology including micrometer ranging, very-high-precision encoders, and multistage pointing actuation. As an example, a three-baseline stellar interferometer concept with short (e.g., 1-meter) to long interferometric baselines has been studied that bring such components together and offers the potential for sub-milli-arcsecond class attitude sensing.[145]

***Status*:** NASA's Deep Space Optical Communications (DSOC) experiment will be the agency's first demonstration of optical communications beyond the Earth-Moon system. The DSOC experiment is piggybacking on NASA's Psyche spacecraft and will demonstrate data communication uplink capability for distances up to 1 astronomical unit from Earth. Future deep-space optical communications technology also has the potential to enable improved interplanetary navigation. Specifically, a range measurement from Earth to the planetary spacecraft should be possible by making use of the measured time-of-flight between uplink pulse and a downlink pulse.

Accuracies on the order of 1 cm will significantly improve on the 1-meter level accuracies currently achieved by radio range measurements. A more detailed discussion how laser-communication technology can be used for metric tracking in support of spacecraft navigation is given in Section 3.3.2 of Part I of this report.[2]

4.2.3 Other GN&C Flight Equipment

Micro-spacecraft GN&C Technology

Micro-spacecraft (e.g., planetary explorers with mass under 100 kg) represent a new opportunity for planetary exploration. Micro-electric propulsion systems are just emerging for CubeSats, and their continued development could eventually lead to future planetary mission applications. The rapid expansion of CubeSat-class terrestrial missions gives rise to the opportunity to potentially use or adapt some of these inexpensive components for deeper space applications. Such components as momentum control devices, star trackers, IMUs, and propulsion systems are among those newly available for spacecraft and can be used if proper caution is exercised, as the quality and expected longevity of CubeSat subsystems are not currently at the level needed for traditional planetary missions. However, the potential exists to utilize this microsatellite equipment at great cost savings, if done carefully and with sufficiently thorough investigation and testing.

***Status*:** Many miniaturized components and subsystems have been developed for CubeSats, and a large number of these devices have already flown. While they may still be of marginal applicability to current planetary missions, their continued growth is encouraged. The field is growing rapidly and may prove to be a source of valuable technologies for future exploration missions.

Radiation-Hardened GN&C Sensors and Avionics

Recent advances in CPU and sensor electronics and software, most notably for smart phone applications, point at potential benefits for deep space applications. Interestingly, some smart phone components are surprisingly radiation tolerant. In other areas, components that are radiation resistant by design are becoming common in the commercial realm as a conventional—and conservative—approach to radiation tolerance. Using software and duplicative software operations on terrestrial electronic components shows great promise as a powerful but inexpensive method for providing avionics radiation resistance. Multi-core architectures, offering multi-parallel-path computing strategies also offer the promise of very robust radiation tolerance, as well as great processor throughput. Planetary missions are being planned that will encounter increasingly challenging radiation environments (e.g., Jupiter and Europa missions) and will likely need to take advantage of all these emerging technologies.

***Status*:** With increasing attention being paid to the radiation-hardness of commercial aircraft and spacecraft avionics, new approaches and products are appearing in the COTS world that may find their way into planetary missions. For the Europa Clipper mission, GNC sensors of very high radiation tolerances have already been developed.

Aeroguidance Control Mechanisms

Various physical methods exist for controlling vehicles in an atmosphere, including center-of-mass adjustment, aeroshell angle-of-attack adjustment, or adjustments of the aeroshell itself, through drag tabs and other means. Furthermore, the flight of aircraft or the (limited) path control of balloons represents a new and scarcely explored field of investigation necessary for a wide range of planetary explorers. Such control mechanisms will be necessary for fully controlled EDL and for vehicles traversing atmospheres, including those of the outer planets.

***Status*:** As discussed earlier, Mars Science Laboratory (MSL) and Mars 2020 have used the same approach for aeroshell entry as used by the Apollo capsules, namely reorienting the lift vector by bank maneuvers. Many other techniques for aeroguidance and control are possible, including attack-angle adjustment of a lifting body, drag-tabs, drag-device control, with many variations. Increasing technology readiness for these types of mechanisms would be valuable for improving vehicle control authority for future EDL missions, as well as for aerocapture into orbits around Uranus and Neptune and their satellites, offering the possibility to significantly increase the delivered mass and reduce time of flight.

Solar Sail Control Mechanisms

Solar-sail control is a field only recently explored, but use of solar sails potentially enables a class of multi-target exploration missions that could obtain great mission duration very economically. The key to such missions is successful and effective control of the main propulsion system—the sail. Many methods have been proposed in theory, with virtually few tried in practice. Shape control of large, ephemeral structures is a new and difficult area of GN&C investigation, and it is one of the prime sail-control methods being considered, but other methods are being formulated, including gimbaled sail-control tabs. Stabilization of such large ephemeral structures is also a GN&C challenge, as is sorting out the rotational dynamics of weak structures of dimensions that could be in the hundreds of meters.

***Status*:** Both the Russian and Japanese space programs have deployed and controlled solar sails in low Earth orbit (LEO) with some success, although the level of closed-loop autonomy for such control has been low. For deep space, as opposed to LEO, that autonomy will need to be improved.

Pulsar Navigation

The OWL report identifies pulsar navigation as a disruptive technology.[1] It is well known that GPS has been used successfully for spacecraft navigation in Earth orbit for many years. Unfortunately, the GPS system does not extend to interplanetary flight due to the poor geometry and significantly reduced signal strength over such long distances. However, pulsars in space provide a very accurate timing reference and can be used in a manner similar to how GPS satellites are used, to enable interplanetary navigation.[146,147] In principle, such an approach could allow a spacecraft to know its position and velocity anywhere in the solar system without requiring ground intervention. Various aspects of pulsar navigation for deep space applications have been studied.[148–150] An overview is given in Section 3.3.3 of Part I of this report series.[2]

Status*:* A proof-of-concept experiment was conducted using the NICER X-ray telescope on the International Space Station (ISS) to demonstrate the application of pulsar-based navigation to an orbiting platform.[151–153] A key limitation of this approach is that a bus-sized X-Ray telescope like NICER would be prohibitive for most planetary spacecraft to carry. Alternatively, one can try to miniaturize pulsar hardware/optics technology to be able to use smaller and more practical pulsar receiver designs. In doing so, a new challenge arises resulting from the significantly reduced signal strength associated with using smaller apertures. In addition to requiring longer in-flight integration times, new algorithms would be needed. In particular, special nonlinear filtering algorithms would need to be developed along the lines of Chen et al.[154] to handle significantly reduced SNR, to solve the underlying multi-hypothesis problem associated with resolving signal phase, resolving integer ambiguity, and also to distinguish background from signal photons. With continued efforts, accuracies on the order of a few kilometers may one day be realized that are largely independent of where the spacecraft is located in the solar system.

Tethered Spacecraft

Space tethers are long thin cables which can be used for propulsion, orbit modification, momentum exchange, reconfigurable structural stabilization and attitude control, and to maintain the relative positioning of the components of a large dispersed satellite/spacecraft sensor system. The field of space tethers has received very considerable attention in recent decades, and some 20 tech demos have already flown, maturing relevant individual component technologies.[155] However, as a space science mission capability, space tethers are currently under-developed and offer an untapped potential across multiple mission domains. For astrophysics[156] and remote sensing,[157,158] space tethered observatories have many advantages compared to monolithic ones and to distributed arrays in terms of providing a reconfigurable baseline, but challenges remain related to dynamic isolation. For planetary in-situ science, space tethers show much promise to enable new types of mission concepts with lower risk sampling operations (being far away from the surface), higher rate of science data quality and return (samples with stratigraphy, sub-surface samples), and much more agility (sampling operations can be repeated multiple times at multiple locations without landing).[159,160] Atmospheric science such as upper atmospheric studies, when large gradients need to be measured, and characterization of Venus and Titan super-rotation requires towing of instrumentation, also enabled by tethers. A concept for deploying a “towbody” from a Venus balloon has been developed, which would enable an instrument platform to be deployed to a high temperature region beneath the clouds.[161] Finally, future underwater science in Ocean Worlds will also need towing underwater devices, also enabled by tethers. Without space tethers in the NASA arsenal of technologies, we will lose future capability to achieve efficient and low-cost space borne distributed spacecraft with variable aperture size from few meters to several kilometers in diameter and the capability for missions requiring towing an instrument, sampling, and delivering and collecting assets from a safe distance.

***Status*:** To date, many in-orbit demonstrators of component technologies involving tethers have flown. However, while many tether technology demonstrator experiments (+20 tether flights) have already flown in Low Earth Orbit (stable tether deployment and retrieval, in-space survivability, tether electrodynamics experiments for power generation), many technologies that could make space tethers very competitive have not yet been tested (orbit modification, tethered payload disturbance mitigation, spinning up or down, payload capture, system retargeting, precision station keeping and vibration control).

4.2.4 GN&C Ground Test Facilities

Free-Flying Propulsion Test Platforms (Short Duration)

Some highly time-critical and large propulsive events can be adequately tested by a realistic high-fidelity simulation. However, EDL is a notable exception where terminal spacecraft control operations are mixed with TRN observations, hazard avoidance, and divert maneuver computations and execution. There is virtually no other way to thoroughly validate these mixed and intense operations than to actually implement them. Propulsive free-flying test platforms are the best means for performing these tests.

***Status*:** Rocket-based test platforms that were used for the Apollo lunar program are beginning to be used again to test complex GN&C and other systems. Some examples are the ALHAT project and the ADAPT project. Also, high-capacity Quadcopters may be used.

Laboratory 6-DOF Emulators

Relatively low-speed GN&C operations can be tested in real time and at real scale, or even scaled in time and space, in flat-floor or 6-DOF robotic arm or gantry simulators. Such simulations provide much (though not all) of the realism of flight. With careful attention to the computer emulation elements, effective and comprehensive tests can be performed with much greater economy than could be provided by a free-flier-based test. Configurations of such test facilities are also generally much more flexible than the independent test craft, although their range of motion is generally far more restricted. These latter restrictions can, to some extent, be overcome through time and space scaling. 6-DOF emulators are also invaluable for testing pointing performance. Spacecraft and payload pointing and stabilization capabilities can be tested in quasi-force-free environments—in or out of vacuum environments—addressing any number and class of perturbations while exploring the coupling of spacecraft and payload. Thermal loading and its effects on critical component alignments can also be tackled allowing critical trades on mass/power vs. complexity of control systems.

***Status*:** 6-DOF emulators and testbeds offer an economical means to test algorithms and even, in the case of outdoor gantries, actual propulsive elements. Such emulators also found use in the Apollo lunar program. Some of them are still available for current-day use. New 3-D-capable and large-scale air-bearing test laboratories have also become available within NASA, offering opportunities to test a number of different mission-relevant GN&C scenarios. Computer simulation also continues to play an important role understanding and testing GN&C operations at realistic time scales. The development of software tools for performing high-fidelity simulation remains an important area for further development. Examples of current tools include DARTS/DSHELL—a multi-mission spacecraft simulation for real-time, hardware-in-the-loop simulations for testing of flight software and hardware[162]; DSENDS—a high-fidelity dynamics and spacecraft simulator for entry, descent, and surface landing[163]; and AMAT—a recent Aerocapture trade evaluation tool to determine the feasibility of aerocapture scenarios.[164]

Aerial GN&C Test Platforms (Long Duration)

Long duration GN&C and operational scenarios can best and most economically be emulated in aircraft flight tests, typically using helicopters and UAVs. Such tests are highly applicable to studying terrain traverses that require landmark-based autonomous navigation with TRN. This is particularly true in studying different scaling regimes where the aircraft are allowed to change altitude in a scaled fashion relative to the prototype scenario. Scaling and emulation will also be necessary with regard to the dynamics of such a simulation. Clearly such flight tests would be less useful for testing spacecraft control laws, since aircraft-generated acceleration profiles are less representative of space operations. However, the economies offered by UAVs make them extremely attractive methods to test the TRN, navigation filtering, autonomy, and operations aspects of many missions and to do so over time spans of only a few hours.

***Status*:** Fully autonomous UAVs offer an increasingly economical means of testing navigation and in some limited instances, G&C algorithms and systems. UAVs are able to cover long distance terrain over long timespans and can make testing of lunar landing, small-body TAG, and orbit scenarios possible in a long-duration scenario.

High-Speed EDL Test Platform

The heavier planetary landers of tomorrow will require much larger drag-increasing devices to slow them down during descent through a thick atmosphere. This applies to both the entry and descent phases of the planetary landing. Such next-generation drag-inducing devices, which include chutes, drag devices, and special lifting bodies, have the potential to improve payload mass delivered to the planetary surface, to reduce achievable landing altitudes, and to improve landing accuracies. A challenge common to all these devices is their need to be deployed at high supersonic speeds to ensure safe landing of the vehicle, crew and cargo. The testing of these components at high supersonic speeds, however, will require very specialized hypersonic test rigs. Deployed from aircraft or from suborbital flights, such relatively expensive test platforms will be invaluable to reducing the risk associated with using these critical drag-inducing elements.

***Status*:** NASA's Low-Density Supersonic Decelerator (LDSD) program had flights in 2014 and 2015 that conducted full-scale stratospheric tests of specific atmospheric drag-inducing components and technologies.[165,166] However, a generic multi-mission supersonic test rig is still lacking and would contribute significantly to validating drag inducing technologies in their application to future landing missions for Mars.

4.3 GNC Methodologies

4.3.1 Uncertainty Quantification

As computing resources become more powerful and less expensive, there are currently efforts to apply advanced Uncertainty Quantification (UQ) techniques to take us beyond "traditional Monte Carlo" frequentist techniques. Sampling methods for inputs can be improved by including approaches that are less "clumpy" and therefore require fewer samples to show representative behavior than pure pseudo-random sampling (e.g., Latin Hypercube sampling). Advanced UQ studies include multidimensional optimization under uncertainty (OUU), hybrid aleatory/epistemic analyses to track the impacts of ignorance in the design, and reliability analysis against specified margins in multiple dimensions. Any frequentist analyses should ideally be accompanied by solution convergence analyses like bootstrapping/jack-knife techniques to assess the variability of reported results as a function of percentile or response value reported. Given that open-source software tools like Dakota from Sandia National Laboratories are now available, management of running simulations to achieve these analyses are now standardized. This alleviates the burden of maintaining that part of the code base from the analyst and the cost of commercial software from organizations.

Traditional Monte Carlo statistical performance analysis can be extended to input/response sensitivity analyses via Sobol indexes, mutual information metrics, and Kolmogorov-Smirnov (K-S) testing techniques. Furthermore, techniques from machine learning like classification trees can be applied to analyze behavioral/non-behavioral performance.

Surrogate modeling techniques like Polynomial Chaos Expansion (PCE) and Kriging methods can ease the computational burden during the analysis and exploration phases. However, when the tail shape of the probability distribution is a driver, it is recommended to ensure that the convergence analysis shows the desired variability at the percentiles specified. Bayesian techniques and implementations can also be considered and implemented for causal operations and new measurements can be used to refine the probabilistic models.

4.3.2 GNC Fault Detection / Protection

The goal of System Fault Protection is to prevent, detect, isolate, safe the spacecraft, and continue the mission autonomously when possible. Prevention of faults happens early in the design phase, from the lowest levels to the highest system levels. The autonomous fault protection system is ideally designed to be integral to the fabric of the system, such that nominal and off-nominal scenarios are addressed, designed, and tested at the same time.[167] This approach ensures that the system can meet the goals of detection, isolation, safety, and mission continuation. This is also the case for the entire control loop, from sensor data acquisition, through all computations, and out to the control element. This integrated approach is critical for reliable GNC performance and has been demonstrated over many years of deep space system design and operations. As an example, the sensor data collection process performs data sanity checking even before computation, with autonomous responses that can either tolerate/remove transient samples or otherwise reliably swap to backup devices. The same is true for the control element, which commands the thrusters and other actuators. Here, detection algorithms monitor thruster executions for errors and halt the operation before it gets out of tolerance. This process is critical to support sensitive controllers like those used by GNC. For the controller alone there are several modes of operation depending on the behavior. An algorithm senses if the goal is on track to be successfully completed and based on progress can alter the behavior, change modes, re-attempt a failed operation, or safe the vehicle to wait for ground intervention when necessary.

Future missions will have even greater challenges, demanding that the GNC systems exercise even greater autonomy. Here robustness and reliability in the system can only be achieved by designing the fault protection system “hand-in-hand” with the nominal algorithms and behaviors.

Status: Fault protection was a critical part of the earliest missions. In the case of Voyager, it was required to autonomously protect all science observations due to their historical importance and rarity.[167] For Deep Space 1, the goal was to demonstrate greater autonomy with the introduction of an onboard navigation system.[169]

More recently, these fault protection algorithms and autonomous behaviors have been incorporated into various different mission phases. For Mars missions, these fault protection behaviors were used for both Cruise phase execution where they enabled autonomous Trajectory Correction Maneuvers and for Entry Descent and Landing to ensure safe landing. Another challenging autonomy application is the ability to gracefully and robustly handle hardware jettison.[170] It is a similar case for the Europa Clipper mission, which must survive around Jupiter in one of the harshest radiation environments in the Solar System. Here, the GNC algorithms and computing system must tolerate the radiation environment, while being capable of autonomously executing the critical orbit insertion burn, as well as executing science observation orbits around Europa. Due to the close proximity of the planned orbits to the Europa moon, the system must have high degree of autonomy and fault protection to reliably perform nominal mission scenarios.

4.3.3 Role of AI, ML, and Deep Learning

Although examples of actual onboard flight realizations are currently limited, the use of Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning is an active area of research in the GN&C community aimed at increasing spacecraft autonomy and solving problems that are difficult to model. Izzo et al.[171] give a comprehensive survey on the application of these methods. Below are some example applications that convey the breadth of possible applications and the value of learning methods to solve challenging problems in spacecraft GN&C.

Deep Learning is especially powerful in image analysis tasks given the typically large amounts of data available for training. For example, in Fragosa et al.,[172] deep learning is applied to generate image features that are invariant to illumination and season, in order to enable a broader application of TRN image matching. A convolutional neural network is applied in Dhamani et al.[173] to localize the Northrop Grumman Enhanced Cygnus vehicle using images from a monocular camera. An important question for planetary exploration is where one can get relevant image data for training. In the case of small body exploration, the AstroVision software application has been recently developed.[174] This is a large-scale dataset comprised of 115,970 densely annotated real images of 16 different small bodies captured during past and ongoing missions. It is used to train a state-of-the-art deep feature detection and description network specifically applicable to small body exploration. The idea would be to replace the human-intensive effort otherwise needed and used to support such missions as OSIRIS-Rex and its touch-and-go (TAG) sample collection event.[175] The development of other similar large-scale datasets could potentially automate the generation of landmark catalogs across other important planetary exploration scenarios as well.

Deep Learning is also useful when models change over time and/or are hard to predict. Silvestrini and Lavagna[176] use reinforcement learning to determine the dynamic model of a formation of micro-satellites to enable more accurate formation control while Neamati et al.[177] use data from past trajectories to learn the gravity field of a small body on the fly.

Guidance is also a fruitful domain for learning due to the difficulty in incorporating constraints while also optimizing for fuel and other metrics. For example, Sánchez-Sánchez and Izzo,[178] use supervised learning to determine optimal guidance trajectories for planetary landing, while Hovell and Ulrich[179] use deep reinforcement learning in simulation to determine guidance laws and then transfer this to real robots in the lab to show successful pose tracking and docking.

Status: The use of AI and Deep Learning by the GN&C research community is growing rapidly across the board. Although actual flight implementation examples are limited, it is anticipated that these techniques will begin to be used in flight missions over the next decade.

5 Findings and Recommendations

In summary, advancement in autonomous GN&C capability, the ability to autonomously manipulate spacecraft trajectory and attitude in reaction to the in situ unknown and/or dynamic environment, is needed. Increased knowledge and modeling of targets, in situ target-relative sensing, estimation, and closed-loop real-time control of the spacecraft with in situ measurements in a real-time dynamic environment will be required. Fuel-efficient autonomous path planning and re-planning will also be necessary. Also necessary is the overall system and software executive technology to enable autonomous execution of the onboard autonomous GN&C functions. As unprecedented levels of autonomous, complex, and stringent performances are being achieved, Earth-based system-level test and demonstration systems have become a necessary part of advancing new concepts with realistic physical dynamics and environment, in addition to the increasingly high-fidelity modeling and simulation. The findings and recommendations below are derived from the previous sections.

5.1 Finding 1

Autonomous onboard GN&C: Advancement in spacecraft autonomous GN&C capability, i.e., the ability to manipulate spacecraft trajectory and attitude autonomously on board in reaction to the in situ unknown and/or dynamic environment, is required for next-generation SMD PSD missions to reach and explore scientific targets with unprecedented accuracies and proximities. Examples include autonomy for Mars Sample Return Lander EDL discussed in Section 3.1.1 and autonomy for Uranus Probe aerocapture discussed in Section 4.1.4.

Recommendation: Develop autonomous GN&C capability, with parallel investments in innovative architectures, innovative and optimized algorithms, advanced sensors and actuators, and system-level demonstrations with relevant physical dynamics and environment conditions. This includes improved capability for EDL (Entry, Descent, and Landing relevant to planets with atmospheres), and DDL (Deorbit, Descent and Landing relevant to planets without atmospheres); Aerocapture performance at Mars, the Ice Giants, and outer planet moons; formation flying for lunar, asteroids/NEO exploration and planetary protection; GN&C for small body proximity operations; and ascent vehicle GN&C and rendezvous & docking to support sample return missions.

5.2 Finding 2

New and advanced GN&C sensors: Innovation and advancement of onboard sensing capabilities are critical, taking advantage of the most recent breakthroughs in component technologies (e.g., autonomous robots, self-driving cars, etc.) and spaceflight-qualifiable computing elements for enhanced onboard instrument analysis capability.

Recommendation: Develop advanced GN&C sensors with direct relevance to future mission needs. Make advancement in individual sensors as well as in integrated sensor systems. With significant advanced computational capability and smaller, less power-hungry sensor components, integration of a few components can serve multiple purposes. GN&C hardware and systems for precision velocity and range sensing are needed to improve navigation accuracy for EDL and DDL. Efforts should be made to reduce the size/mass/power of terrain-relative sensors (cameras, lidar, altimeters, radars, etc.), improve radiation hardness, and lower component/system integration costs.

5.3 Finding 3

New and advanced GN&C algorithms: GN&C algorithm development is needed in parallel with advancements in hardware, software, and architecture. Examples include 6DOF coupled guidance algorithms for close-proximity operations (cf., Section 4.1.1), control algorithms for low thrust SEP spacecraft for outer planet exploration with increasingly large solar panels and lightly damped flex modes (cf., Section 4.1.1), and advanced flight control algorithms for future more capable Mars helicopters (cf., Section 4.1.3).

Recommendation: Develop algorithms for innovative solutions to GN&C challenges, e.g., fuel-optimal, real-time GN&C solutions, new techniques and approaches that enable much greater landing accuracy, and fusion of data from multiple sensor sources for superior estimation of spacecraft states. Emphasis should be placed to address situations with tight time constraints (e.g., responding to late-breaking navigation updates for improved Aerocapture), high dynamics (alternative/Skycrane-style planetary landings, rotorcraft dynamics), guided trajectories through atmospheres (hypersonic entry, EDL, Aerocapture), high disturbance environments (hovering over plumes on Enceladus, Titan probes/flybys, comet outgassing), maneuvering in close surface proximity (e.g., small body exploration), and integrated onboard 6DOF control of the trajectory and attitude of the spacecraft. To be most effective, algorithms should be developed in parallel with new architectures, hardware, and software.

5.4 Finding 4

Testing capabilities are critical and need to be improved. As more complex systems with stringent performance requirements are pursued, end-to-end system-level modeling, as well as testing and simulation are required to flight-qualify newly developed system-level capabilities achieved through incorporation of new technology elements.

Recommendation: Continue to advance integrated modeling and simulation at the mission capability level, with increasing fidelity that matches advancements in component technologies. Develop system-level demonstration systems, such as ground based end-to-end GN&C system testbeds, aerial field tests, sounding rockets tests, and free-flying-vehicle-based, closed-loop GN&C system tests.

5.5 Finding 5

There is substantial commonality in GN&C technology needs across missions. GN&C components and systems can be developed and deployed across multiple mission types more effectively and economically than point-design solutions engineered for individual mission scenarios.

Recommendation: Attention should be paid to GN&C *systems*, not just the individual algorithms, hardware, and software subsystems, because this will allow for reasoned cross-cutting trades across functions and missions. PSD can provide incentives in the structure of announcements of opportunity such that feed-forward of developments for one project to the next are maximized.

5.6 Finding 6

General onboard spacecraft autonomy: Onboard autonomous GN&C is a significant part of overall spacecraft autonomy. It is closely related to advancement in areas of onboard planning; re-planning; and fault detection, identification, and recovery.

Recommendation: GN&C technologists need to stay current with advancements being made in the related fields of general onboard autonomy and onboard planning; re-planning; and fault detection, identification, and recovery. This would be best achieved through regular targeted workshops where NASA GN&C technologists would invite leading technologists in other fields to explore technology-transfer opportunities.

5.7 Finding 7

Planetary Defense is a relatively new and important area described in the Planetary Sciences Decadal Survey to mitigate the threat from potentially hazardous Near-Earth Objects (NEOs) impacting Earth. Onboard GNC capabilities are needed that enable NEO flyby, characterization, target intercept, rendezvous, and kinetic impact/nuclear-based mitigation scenarios.

Recommendation: Develop precision terminal GNC algorithms and associated spacecraft systems for hypervelocity flybys/intercepts to enable accurate and reliable targeting of small NEOs at closure speeds of up to 20 km/s. Ion beam deflection and gravity tractor methods require GNC capabilities that enable the spacecraft to formation fly with the NEO, performing close, autonomous, and extended proximity operations to station keep at a predetermined distance from the target body. The onboard GNC system must also be tolerant of technical system faults and unexpected NEO physical characteristics including tumbling, outgassing, mass expulsion, and hazards from orbiting bodies/moons.

5.8 Finding 8

Advanced navigation technology for EDL/DDL: An important goal for future planetary exploration is to precisely land payloads while simultaneously avoiding landing hazards. Terrain Relative Navigation (TRN) is an important localization capability that provides a map-relative position fix that can be used to accurately target specific points on planetary surfaces. Hazard Detection and Avoidance (HDA) is an important landing function that uses data collected on board to identify safe landing sites in real time as the vehicle descends. As examples, TRN will be needed for Mars Sample Return EDL as discussed in Section 3.1.1, and HDA will be needed for the Dragonfly rotorcraft mission to Titan (cf., Section 5.2.4, Part IV of this report series).[4]

Recommendation: Develop algorithms and processes for TRN and HDA to improve EDL/DDL landing precision as well as to avoid large-scale surface hazard regions observed in reconnaissance maps. At lower altitudes and closer ground proximity, algorithms and processes for real-time map generation should be developed to support precision TRN and to enable HDA to avoid small-scale surface hazards while finding regions suitable for safe landing. Relevant special topics include the development of long-range lidars, the ability to land in the dark, illumination insensitive landmark matching, cross-modality feature matching (e.g., visible and SAR), and potentially a “fully autonomous” bolt-on type TRN sensor system that produces position/pose estimates without requiring inputs from the host spacecraft. For example, it could provide its own position/velocity information for initialization, produce its own attitude knowledge throughout, and run on its own stand-alone computational platform.

Acronyms

ADAPT	Autonomous ascent and descent powered-flight testbed
ADEPT	Adaptive deployable entry system project
AI	Artificial Intelligence
ALHAT	Autonomous Landing Hazard Avoidance Technology
AMAT	Aerocapture Mission Analysis Tool
APL	Applied Physics Laboratory (Johns Hopkins)
AR&D	Autonomous rendezvous and docking
ARPOD	Autonomous rendezvous, proximity operations, and docking
AutoNav	Autonomous navigation
CCD	Charge Couple Devices
COTS	Commercial, off-the-shelf
CONOPS	Concept of operations
CMOS	Complementary metal-oxide semiconductor
CPU	Central processing unit
DARPA	Defense Advanced Research Projects Agency
DARTS	Dynamics algorithms for real-time simulation
DSHELL	DARTS Shell
DSENDS	Dynamics and spacecraft simulator for entry, descent, and surface landing
DDL	Deorbit, descent, and landing (for planets with no atmospheres)
DI	Deep Impact
DOF	Degrees of freedom
DS1	Deep Space 1
DSAC	Deep Space Atomic Clock
ECLSS	Environmental control and life-support system
EDL	Entry, descent, and landing (for planets with atmospheres)
EDD	Entry, descent, deploy (aerial vehicles)
EP	Electric propulsion
ESA	European Space Agency
FDIR	Fault detection, identification, and recovery
FOV	Field of view
G&C	Guidance and control
GEO	Geosynchronous orbit
GN&C	Guidance, navigation, and control
GPS	Global positioning system
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	Gravity Recovery and Climate Experiment-Follow On
GSFC	Goddard Space Flight Center
HA	Hazard avoidance
HDA	Hazard detection and avoidance
HEOMD	Human Exploration and Operations Mission Directorate
HIAD	Hypersonic inflatable aerodynamic decelerator
HRN	Hazard-relative navigation
IMU	Inertial measurement unit
InSAR	Interferometric synthetic aperture radar
ISS	International Space Station
IR	Infrared
JPL	Jet Propulsion Laboratory
LDSD	Low-Density Supersonic Decelerator
LEO	Low Earth orbit

Lidar	Light detection and ranging
LVS	Landing Vision System
MER	Mars Exploration Rover
MEMS	Micro-electromechanical systems
ML	Machine Learning
MSL	Mars Science Laboratory
M2020	Mars 2020
MSR	Mars sample return
NASA	National Aeronautics and Space Administration
NEO	Near-Earth object
NICER	Neutron star Interior Composition Explorer
OCT	Office of the Chief Technologist
OUU	Optimization under uncertainty (OUU)
OWL	Origins, Worlds, and Life (decadal report)
PCE	Polynomial Chaos Expansion
PRISMA	Prototype Research Instruments and Space Mission Technology Advancement
PSD	Planetary Science Division
Radar	Radio detection and ranging
RDF	Radio direction finder
SEP	Solar electric propulsion
S/C	Spacecraft
S/W	Software
SAR	Synthetic aperture radar
SMD	Science Mission Directorate
SWaP	Size, weight, and power
TAG	Touch and go
TERCOM	Terrain continuous matching
TPS	Thermal-protection system
TRL	Technology readiness level
TRN	Target-relative navigation
UAV	Un-crewed aerial vehicle
UQ	Uncertainty Quantification
VO	Visual odometry
VIO	Visual Inertial Odometry

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