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

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

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National Aeronautics and
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Jet Propulsion Laboratory
California Institute of Technology
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Part II. Onboard Guidance, Navigation, and Control (GN&C)

Strategic Missions and Advanced Concepts Office
Solar System Exploration Directorate
Jet Propulsion Laboratory
for
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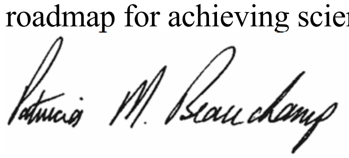
Foreword

Future planetary explorations envisioned by the National Research Council's (NRC's) *Vision and Voyages for Planetary Science in the Decade 2013–2022*, developed at the request of NASA the 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 defined to be the onboard determination of the desired path of travel from the vehicle's current location to a designated target. *Navigation* is defined as the science behind transporting ships, aircraft, or spacecraft from place to place; particularly, the method of determining position, course, and distance traveled as well as the determination of the time reference. *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 demands on GN&C increase, and so continuous technology progress is necessary. Recognizing the significance of this research, the NRC of the National Academies listed many GN&C technologies as top priorities in the recently released *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*.

This document—Part II, Onboard Guidance, Navigation, and Control—is the second in a series of three technology assessments evaluating the capabilities and technologies needed for future missions pursuing SMD PSD's scientific goals. 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 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). Part II, Onboard Guidance, Navigation, and Control, 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 entry, descent, and landing, in some planetary missions). Part III, Surface Guidance, Navigation, and Control, examines GN&C for vehicles that are not in free flight, but that operate on or near the surface of a natural body of the solar system. Together, these documents provide the PSD with a roadmap for achieving science missions in the next decade.



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Other Reports in This Series

Power Technology

- Advanced Radioisotope Power Systems Report, Report No. JPL D-20757, March 2001.
- Solar Cell and Array Technology for Future Space Missions, Report No. JPL D-24454, Rev. A, December 2003.
- Energy Storage Technology for Future Space Science Missions, Report No. JPL D-30268, Rev. A, November 2004.

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Extreme Environments Technology

- Extreme Environment Technologies for Future Space Science Missions, Report No. JPL D-32832, September 2007.
- Assessment of Planetary Protection and Contamination Control Technologies for Future Science Mission, Report No. JPL D-72356, January 2012.

Guidance, Navigation, and Control Technology

- Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions: Part I. Onboard and Ground Navigation and Mission Design, Report No. JPL D-75394, October 2012.

In Preparation

Guidance, Navigation, and Control Technology

- Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions: Part III. Surface Guidance, Navigation, and Control

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Executive Summary

This document "Onboard Guidance, Navigation, and Control," is the second in a three-part series assessing the guidance, navigation, and control (GN&C) capabilities and technologies needed for future mission concepts developed at the request of the Science Mission Directorate (SMD) Planetary Science Division (PSD).

Onboard GN&C is defined to be the path planning, sensing, and control of the spacecraft to achieve desired spacecraft maneuvers and pointing. GN&C functions largely occur on board 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. *GN&C flight instruments* can be divided into target-relative and inertial sensors. Target-relative sensors include landmark-relative position estimation, aeroguidance, LIDARs, hazard detection and avoidance, and precision pointing control. Inertial sensors include star-trackers, gyros, and accelerometers, as well as precision time determination. *Non-sensing GN&C flight hardware* includes microspacecraft 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 to future aggressive and rewarding PSD missions, including operations in time-urgent, 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. Further, these challenges are met in a wide variety of mission scenarios, including surface landing in high or low gravity, in high or low atmosphere, 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.

GN&C has progressed very far during 60 years of space flight, but not enough to perform many of the upcoming missions. Technology investments need to be made in on-board GN&C in order to accomplish the missions proposed for the next decade. The use of these technologies, facing these challenges in these scenarios, was analyzed for the missions recommended in the Planetary Science Decadal Survey (see Appendix B of this document). The missions considered are Mars sample return (MSR), comet surface sample return, lunar south-pole Aitken Basin sample return, Saturn probe, Trojan tour, Venus *in situ* explorer, Io observer, Lunar geophysical network, Titan Saturn system mission, Jupiter Europa orbiter, Uranus orbiter and probe, Europa orbiter, Neptune orbiter and probe, Ganymede orbiter, Europa lander, near-Earth object (NEO) surveyor or explorer, and Mars geophysical network. It also covers potential Discovery-class missions.

The summary table below shows the results of these analyses, prioritizing technology development based on likely frequency of use ("raw prioritization"), and then qualified by

estimated cost of development ("cost-moderated prioritization"), considering current technology readiness level (TRL). Fortunately, the ratings remained very similar under both rating criteria.

Summary Table. Results of technology assessment for missions recommended in the 2011 Planetary Science Decadal Survey (prioritization by frequency of potential use, and by frequency amplified by cost and technical maturity; same as Table 5-1).

Cost-Moderated Prioritization \ Raw Prioritization	Highest Priority	High Priority
Highest Priority	6-DOF G&C, nonlinear path planning, integrated GN&C software systems, target-relative position and attitude estimation, nano-g accelerometers, advanced onboard computation	Low-thrust guidance, terrain sensors
High Priority	Aerial platform GN&C emulators	Microspacecraft GN&C technology, precision planetary pointing systems, altimetry and velocimetry, hazard-detection sensors, free-flying propulsive platforms, laboratory 6-DOF emulators

As well as the above prioritizations, a number of findings and recommendations were made:

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 aimed to reach and explore scientific targets with unprecedented accuracies and proximities (Section 4.1.1).

Recommendation: Invest in 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.

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 such as LIDARs and spaceflight-qualifiable computing elements for enhanced on-instrument analysis ability (Section 4.2).

Recommendation: Invest in 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. For example, a camera, a LIDAR, an inertial measurement unit (IMU), and a computer can constitute an integrated sensor system that provides altimetry, velocimetry, target-relative navigation, and hazard detection—one sensor system replacing four sensor systems.

Finding 3

New and advanced GN&C algorithms: algorithms in guidance, estimation, and control are needed in parallel with advancements in hardware, software, and architecture (Section 4.1).

Recommendation: Invest in 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. Algorithms must be developed in parallel with new architectures, hardware, and software.

Finding 4

Onboard GN&C is performed by systems and not just components. As more complex systems with stringent performance requirements are pursued, the interplay across components, flight dynamics, and physical environment increases. System-level physical test and demonstration systems are necessary (Sections 4.1.1.4, 4.2.4).

Recommendation: Invest in 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.

Finding 5

Testing capabilities are critical and need to be improved. End-to-end system-level modeling, testing, and simulation are required to flight-qualify newly developed system-level capabilities achieved through incorporation of new technology elements (Section 4.2.4).

Recommendation: Continue to advance integrated modeling and simulation at the mission capability level, with increasing fidelity matching advancements in component technologies.

Finding 6

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. SMD provide incentives in the structure of announcements of opportunity such that feed-forward of developments for one project to the next can be maximized.

Finding 7

General onboard 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 (Section 4.1.1.3).

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 workshops where NASA GN&C technologists would invite leading technologists in other fields to explore technology-transfer opportunities.

Finding 8

GN&C commonality across NASA: There is much to be learned within the human spaceflight program from GN&C experience in SMD. Though the scales are vastly different, the methods and technologies are the same. For this reason, there should be substantial opportunities for SMD and the Human Exploration and Operations Mission Directorate (HEOMD) to cooperate on mutually beneficial GN&C technology and subsystem development.

Recommendation: Assign a task to the NASA Engineering and Safety Center GN&C Working Group/Community of Practice to identify cross-cutting GN&C technologies across the human and robotic exploration programs, and propose strategies for common development. Such a catalog and strategy should inform future technology plans for both the human and robotic programs and will be of substantial benefit to NASA.

1 Relationship of This Document to the NASA Office of Chief Technologist Technology Roadmaps

The NASA Office of Chief Technologist (OCT) has recently completed an extensive evaluation of NASA technology needs. These results have been published in the document, *NASA Space Technologies and Roadmaps and Priorities; Restoring NASA's Technological Edge and Paving the Way for a New Era in Space,* published by the National Academy of Sciences (NRC), Aeronautics and Space Engineering Board, Division on Engineering & Physical Sciences, January 2012. This report, developed by over a dozen panels and over many dozens of individual technology areas, identified GN&C as a prime area of technology investment need for NASA. The technology prioritization is presented in a table in the report summary, which lists the highest value/priority technology investment areas as a function of broad agency objectives; this table is reproduced in this document as Table 1-1.

The importance of GN&C technology in NRC's overall technology assessment is clear, with GN&C technology placing in the top priority list for two of the three NASA Objective areas, and placing first in one of them, Objective B, "Explore the evolution of the solar system and the potential for life elsewhere." The finding is in alignment with the current assessment for Spacecraft Onboard GN&C needs for SMD PSD; this document details the technologies required for upcoming planetary missions.

Table 1-1. Final prioritization of the top technologies, categorized by objective.[1]

Technology Objective A Extend and sustain human activities beyond low Earth orbit	**Technology Objective B** Explore the evolution of the solar system and the potential for life elsewhere (in situ measurements)	**Technology Objective C** Expand understanding of the Earth and the universe (remote measurements)
Radiation mitigation for human spaceflight	GN&C	(Instruments and sensor) optical systems
Long-duration (crew) health	Solar-power generation (photovoltaic and thermal)	High-contrast imaging and spectroscopy technologies
Environmental control and life support systems (ECLSS)	Electric propulsion	Detectors and focal planes
Guidance, navigation, and control (GN&C)	Fission (power)	Lightweight and multifunctional materials and structures
Thermal propulsion	EDL TPS	Active thermal control of cryogenic systems
Lightweight and multifunctional materials and structures	*In situ* instruments and sensors	Electric propulsion
Fission (power)	Lightweight and multifunctional materials and structures	Solar-power generation (photovoltaic and thermal)
Entry, descent, and landing (EDL) thermal protection systems (TPS)	Extreme terrain mobility	

Note: [1]Table 3.8 from *NASA Space Technologies and Roadmaps and Priorities—Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*. Reprinted with permission from the National Academies Press, Copyright 2012, National Academy of Sciences. Red circles added by author for emphasis—the solid circle highlights technology discussed in this document, having particular relevance to the missions of the Planetary Science Division; the dotted circle pertains mostly to the Human Exploration and Operation Mission Directorate (HEOMD), and so is not as strongly applicable to this document, but still somewhat relevant.

2 Spacecraft Onboard GN&C—Definition of Terms, and Principal Motivations

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 maintain vehicle pointing with the required precision, and simultaneously—when necessary—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.

GN&C has progressed in the 60 years of space flight but not enough to perform upcoming missions. Technology investments need to be made in on-board GN&C in order to accomplish the missions proposed for the next decade. To reach and explore the new scientific targets of SMD PSD interest, advances in GN&C capabilities are needed for the following mission scenarios, which will be described in the next section:

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

Very significantly advanced GN&C performance is needed to overcome the following natural challenges:

- Long round-trip light time
- Time urgent *in situ* operations
- Unknown and dynamic environment
- Flight and mission system fault conditions
- Mission longevity

These challenges that apply variously to some or all of the above scenarios will drive the development of GN&C technology across the full span of functions, as will be discussed in the following sections.

3 Future Mission Scenarios Requiring Advanced Onboard GN&C

The future missions called out in the 2011 Planetary Science Decadal Survey and major concept studies are summarized in Appendix A. In this section, the corresponding mission scenarios and the related GN&C capabilities needed for these scenarios are described and discussed in narrative, with particular attention to needed new technology for their implementation. The specific relationship between future mission scenarios and the GN&C technologies is fully laid out tabularly in Appendix B, but summarized in Section 5.

3.1 Surface Landing Missions

3.1.1 Landing on Mars

Relevant future missions: Mars Sample Return (MSR), Mars NetLander, and future Mars rovers

Landing on Mars requires fully autonomous GN&C with linked attitude and trajectory guidance running on very-high-frequency, closed-loop control due to a highly dynamic environment, high gravitational forces, and atmospheric perturbations (Figure 3.1.1-1). 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 intensify for every new Mars landing.

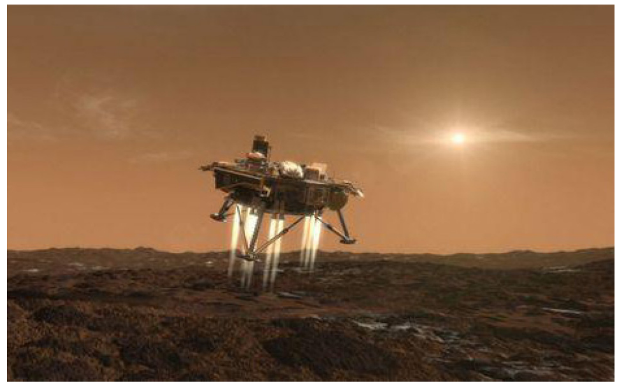

Figure 3.1.1-1. A Phoenix-derived Mars Sample Return (MSR) concept shown performing precision landing on Mars in an artist's concept.

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 are new capabilities in the atmospheric entry phase that will directly facilitate improvements in landing accuracy and delivered mass of next-generation missions. The combination of improved pre-entry navigation and intelligent use of nano-g accelerometers can lead to dramatic targeting improvements at landing. Alternatively, in the powered descent and landing phase starting after parachute deployment, landmark-based navigation, with target-relative navigation (TRN), determining the offset to the target, followed by a large trajectory deflection to fly out vehicle offset from target, will enable very precise landing. With current technology, the divergence from the desired landing site at the end of the atmosphere entry phase is relatively large (e.g., 4–8 km at Mars) due to atmospheric perturbations. This large offset is one reason that missions require such large safe landing areas, within which they must subsequently "rove" to sites of scientific interest.

When pre-landing surveys are inadequate to guarantee terrain safety, hazard detection and avoidance (HDA) will be increasingly necessary for autonomous safe landing. Thus, some combination of improved pre-entry navigation, accelerometry, onboard landmark-based autonomous navigation with TRN, fuel-optimal large trajectory deflection guidance (path planning), and HDA will be needed for landing accuracy improvements. Using these methods, almost arbitrary landing accuracy will be possible enabling the positioning of a landed asset directly in a region of high science interest. These advanced systems will depend upon a high degree of interplay across the sensors, actuators, algorithms, and software, necessitating comprehensive iterative testing and demonstration at the system level in testbeds; Earth-based, free-flying, closed-loop demonstrations; and other realistic simulated environments.

Once landed, rovers will use a number of methods for surface navigation; these topics are covered in Part III of this series, "Surface Guidance, Navigation, and Control."

3.1.2 Landing on Bodies with Significant Gravity and No Atmosphere

Relevant future missions: Lunar south pole–Aitken Basin sample return, Lunar geophysical network, Europa lander, NEO surveyor or explorer

Robotic landing on large surfaces without atmosphere (e.g., the Moon) is less challenging than landing on Mars. Atmospheric uncertainties are not present and the target site is visible starting from very high altitudes with no entry "plasma phase" to block the view. Landmark-based autonomous navigation, with TRN and HDA are still necessary to reach critical landing sites of high scientific interest but surrounded by terrain hazards (Figure 3.1.2-1).

Figure 3.1.2-1. A concept heavy cargo-carrying lunar lander, shown re-supplying bases on the Moon.

3.1.3 Surface Landing on Low-Gravity, Small-Body Targets

Relevant future missions: Comet surface sample return, NEO reconnaissance, planetary defense, martian moon exploration

Low-gravity landing differs fundamentally from high-gravity in the time-scales and requirement for high thrust, as well as the need for closely operating trajectory and attitude-control loops (Figure 3.1.3-1). Many missions to low-gravity targets will make multiple landings, and so will require landing and ascent capability. By definition, an atmosphere is not an issue at these targets, and with all "airless" landings, visibility of landmarks on the surface is continuous (if lighting is appropriate). Though much simpler than high-gravity EDL, low-gravity EDL can still require complex and time-critical combined trajectory and attitude control to gather a sample without making damaging contact with the surface, particularly if the spacecraft needs to remain fully functional for repeated descent, landing, and ascent cycles.

Figure 3.1.3-1. A small body explorer preparing to make contact on a small asteroid.

An important characteristic of these missions is the lack of *a priori* information about the body. In particular, detailed maps will be required to undertake the landmark-based navigation (TRN) as well as detailed gravity models. In general, this requires an extensive ground campaign to develop these maps in a process that can be highly labor intensive. This key element of navigation technology is discussed in Part I of this series, "Onboard and Ground Navigation and Mission Design."

3.1.4 Landing on Titan and Venus

These two bodies, 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 mechanisms on the parachute or balloon. The navigation of such descent trajectories is done with imaging (TRN) or radiometrics, using one-way data from Earth and a precision clock-reference on the vehicle, or to an orbiting relay craft (Figure 3.1.4-1)

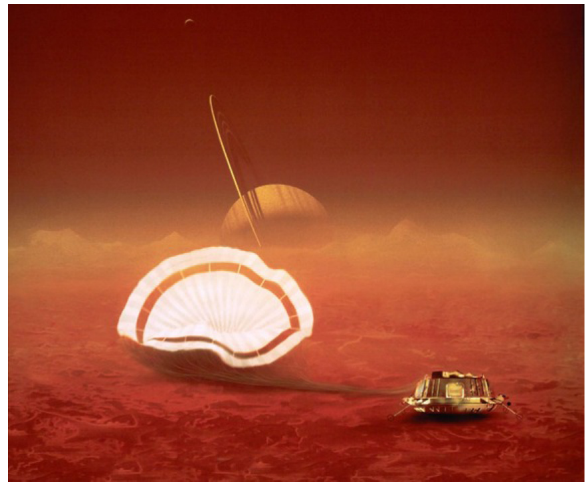

Figure 3.1.4-1. Artist rendering of a Titan probe.

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

Relevant future missions: Comet surface sample return, Trojan asteroid tour and rendezvous, Mars moon exploration

Key characteristics of small-body targets are 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 ascent, 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, except in the case of comets, which produce an outgassing atmosphere that at times can be substantially obscuring. Controlling the spacecraft to avoid contact with the surface during proximity operations is one of the critical requirements for this mission type. Additional challenges may arise from forces due to ejected material and gas. Unknown and complex gravity models and dynamics of the target body are effective perturbing forces that must be countered, while still maintaining landing accuracy and safety. Science requirements to avoid disturbing or contaminating the surface with propellant often add severe GN&C constraints that must also be overcome (Figure 3.2-1).

Figure 3.2-1. Conceptual mission performing proximity operations at a small body.

A key dynamic attribute of such missions is "terramechanics," that is, interaction with surface material that can vary in strength and density by orders of magnitude between asteroids and comets. These factors of surface compliance, which affect extension and support mechanisms as well as immediate contact devices, are treated in Part III of this series, "Surface Guidance, Navigation, and Control."

All of these missions require complex approach, rendezvous, and survey phases, entailing inertial navigation and terrain model development, which is covered in Part I of this series. Similarly, Part I describes the technologies required for the orbital phase of the mission design.

Multiple forms of proximity operations and surface approaches are under examination, including touch-and-go (TAG); open-loop close flyby; and harpoons, darts, and others. These share, in various combinations, phases of operation including approach, descent, hovering, ascent, pursuit, and capture.

- TAG entails a "soft" and short landing operation, where a sampling probe, rather than the entire spacecraft, makes contact with the target body. 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. Fault detection, identification, and recovery (FDIR) will be a key component of TAG, as the spacecraft has the ability to make multiple TAGs, and has to survive each, or abort and try again if conditions are anomalous.
- Close flyby approaches feature open-loop control of the trajectory from the ground and target for a close-proximity flyby.
- A harpoon approach keeps the spacecraft hovering at a further distance than does TAG and uses a longer, flexible appendage from the spacecraft to anchor and retrieve the sample. This method may be simpler from a GN&C standpoint, as it reduces surface transmission forces and torques to the spacecraft.
- The impactor collection approach involves collecting cored samples from the surface with a device such as a mechanical dart, and retrieving the ejected sample canister via Autonomous Rendezvous and Docking (AR&D) functions. Coring darts can be tethered or free. 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, 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.

These 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.

3.3 Sample-Return Missions

Sample-return missions from the different targets in our Solar System may take one of several forms, all requiring advanced GN&C skills. As currently envisioned, MSR will loft a sample into orbit from a surface rover, requiring the capturing craft to perform AR&D operations. A primitive-body sample return might require a TAG operation that is in some ways a very soft landing, with an immediate ascent, featuring the challenges of a low-gravity lander, plus other challenges associated with a brief grazing contact. This is the approach to be taken by the currently developing Osiris ReX mission. Other sample return missions may be MSR-like, with direct-to-Earth return, requiring onboard navigation ability to achieve a highly fuel-constrained return trajectory. Still others may use dart-like projectiles to mechanically take a sample and eject it back toward the waiting spacecraft, requiring an MSR-like AR&D 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. Such missions would likely require highly reliable interplanetary autonomous navigation, for communication with the spacecraft in deep space would be impracticable (Figure 3.3-1).

Figure 3.3-1. Concept for a Mars Ascent Vehicle (MAV) launch for a possible MSR mission.

3.3.1 Ascent, Autonomous Rendezvous and Docking (AR&D), and Sample Return

Relevant future missions: MSR, comet surface sample return

AR&D requires tightly integrated suites of GN&C capabilities, including vehicle-landmark-based navigation, imagers, proximity/range sensors (e.g., LIDAR and RADAR), and generic GN&C autonomy. Ascent is included with AR&D in this subsection because planetary missions requiring an ascent phase are typically ascending to rendezvous with another craft (e.g., the Apollo missions). The ascent phase becomes the first phase of an AR&D operation and is actually not a distinct operation. Sample return is included here because some sample-return scenarios (e.g., MSR) include an AR&D component. Though the autonomous GN&C systems applied to AR&D are tuned specifically for an AR&D operation, they do share much, if not all, of the nature of a generic autonomous GN&C capability, including image/range processing, orbit determination and maneuver calculation. In addition, the generic autonomy of sequence and control is required, as is FDIR. However, the tuning for AR&D, and requirements for AR&D operations testing and simulation, are fairly specific. It is also important to note that AR&D functions divide into two importantly different classes, rendezvous with cooperative targets vs. rendezvous with uncooperative targets. Apollo and MSR are examples of the former whereas docking with orbital debris or automated satellite rescue are examples of the latter (Figure 3.3.1-1).

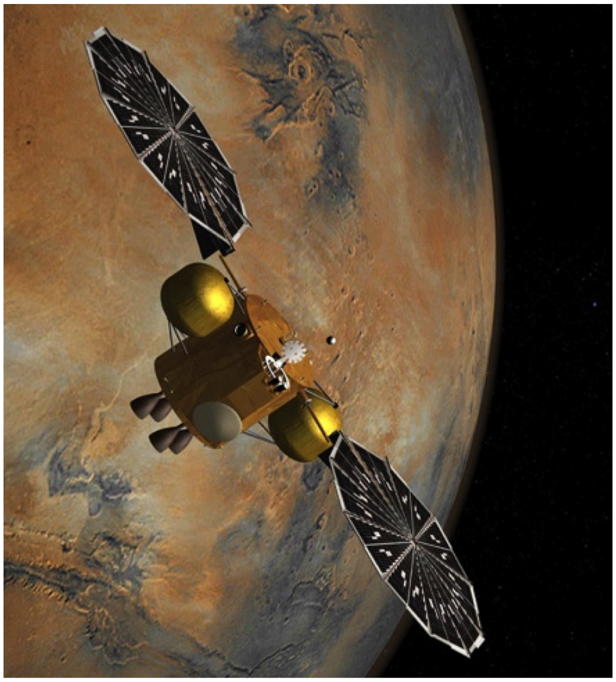

Figure 3.3.1-1. Notional capture and return ship in the rendezvous phase of a possible MSR mission.

3.4 Multiple-Target Planetary Tours

Relevant future missions: Titan, Enceladus, and Saturn system mission, Europa orbiter/lander

A multi-target solar-system tour (e.g., of asteroids) is likely to be a low-thrust mission, and require some onboard ability to cope economically with the intense activity of electric propulsion over long cruise times. 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 (Figure 3.4-1).

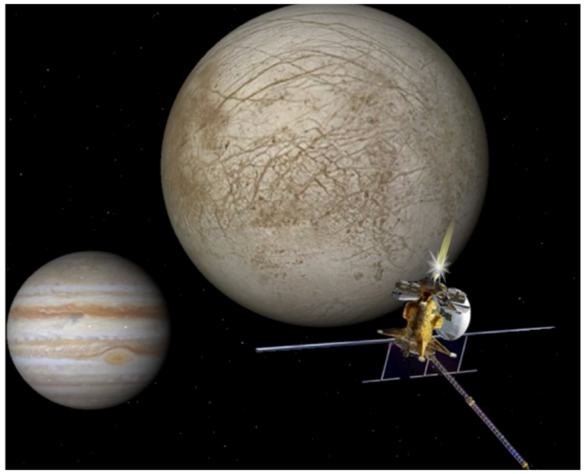

Figure 3.4-1. Concept "Europa Clipper" mission in synchronous orbit around Jupiter enabling multiple close flybys of Europa.

3.5 Planetary Orbiter

Relevant future missions: Jupiter Europa orbiter, Uranus orbiter and probe, Io observer

Though planetary orbiters have been successful without extensive autonomous onboard GN&C, future missions with more demanding requirements will feature such systems. With landmark- and TRN-based autonomous onboard GN&C, orbiters can maintain their own orbits. At Mars, autonomous aerobraking will save considerable operations costs. Autonomous aerobraking systems are closely related, if not identical, to autonomous onboard GN&C systems. Autonomous navigation, combined with automated event planning and sequencing, will greatly aid the mapping of bodies, or the high-resolution targeting of specific locations, or even the identification and targeting of newly arising features of interest. A concept Neptune orbiter is shown in Figure 3.5-1.

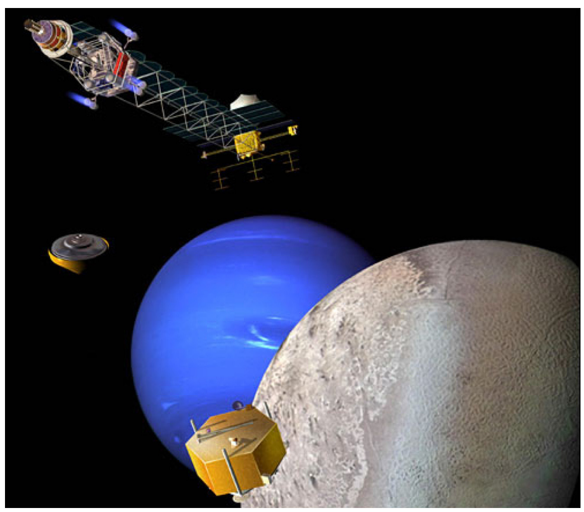

Figure 3.5-1. Notional concept for a nuclear-electric Neptune orbiter.

For orbiting or flybys of planetary targets with high radiation (e.g., Europa), innovative GN&C sensor/actuator technologies and shielding approaches should 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.

3.6 Formation Flying and Spacecraft Swarms

Relevant future missions: Magnetosphere and gravity missions, and fields/particles samplers

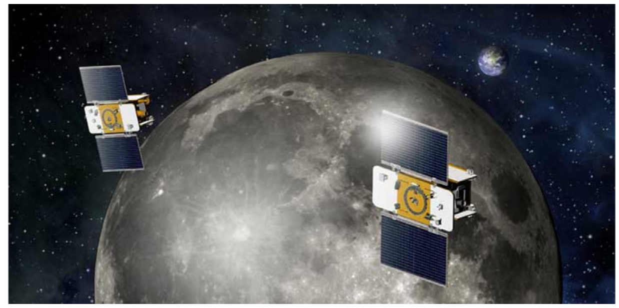

Figure 3.6-1. The GRAIL mission is a recent example of the utility of formation flying concepts to planetary science.

Holding multiple spacecraft in relative formation and maintaining a "swarm-pattern" are two distinct path-patterns of swarm operations. These flight configurations require precision methods of inter-vehicle metrology, from micrometer-class to meter-class. The former can be achieved with radio or infrared links, whereas the latter can be done passively with imagers. With distributed operations among the formation or swarm, independent position and attitude estimation may be required in addition to relative position estimation. Depending on the number of spacecraft and patterns to be flown, the guidance algorithms and control systems could require sophisticated use of generic autonomy and FDIR capabilities. Though applications for formation flying and swarms technology have limited immediate application to *in situ* planetary exploration, such architectures will likely find a home in PSD in the future, and advantages of simultaneous multisite investigation (e.g., of magnetospheres and atmospheres) as well as remote interferometric observations will likely be seen in the future. Figure 3.6-1 shows the GRAIL spacecraft, which returned important lunar gravity science via formation-flying.

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

GN&C onboard 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. The first two can be, in turn, subdivided into inertial-based subsystems (e.g., those using inertial coordinates, computations, or sensing) and target-relative-based subsystems (e.g., those making or making use of target-body [either natural or artificial] landmark measurements, coordinates, and computations). Figures 4-1 and 4-2 show the interaction and command and data flow between these GN&C technology elements. Following are brief descriptions of these technology areas.

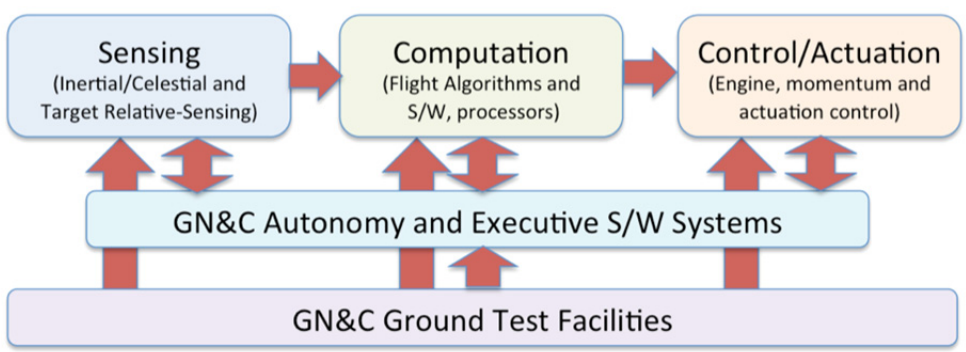

Figure 4-1. High-level interaction of GN&C technology categories.

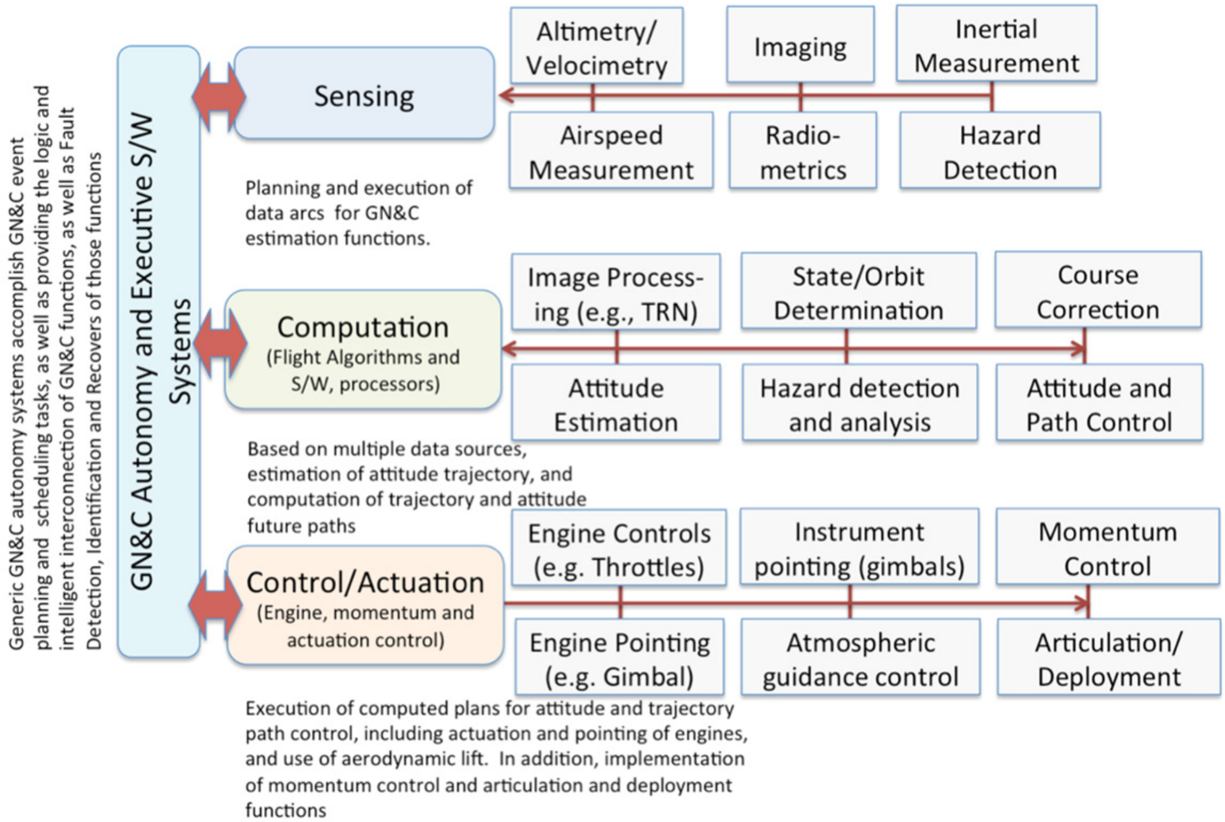

Figure 4-2. GN&C technology element data and function flow for a complex GN&C system, such as for EDL.

4.1 GN&C Flight Algorithms and Software

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

4.1.1.1 6-DOF G&C

When trajectory control is tightly linked with attitude control, which is the case for prolonged thrusting, attitude and trajectory control loops must often be partly or entirely combined. This is certainly the case for powered descent to the surface of a large body, such as the Moon or Mars. However, 6-DOF G&C (3 DOF for position, 3 for attitude) is often necessary for cases of brief TAG contact with a low-gravity body, where long ascent thrusts may have to be combined with preservation of the desired safe attitude to prevent vehicle contact with the surface of the target body (depending upon the strength of the thrusters used). With high-gravity descent using pinpoint control, large powered divert trajectories—necessary to remove late-sensed position errors or implement hazard avoidance—fuel-optimal G&C may be necessary because the potential divert range is always very limited. AR&D will require only loosely coupled position and attitude control because of the generally slow time constants involved in rendezvous and docking.

Status: 6-DOF G&C has been used in space applications for high-propulsion events such as the Apollo landings, and for several propulsive Mars landings, which featured minimal specific trajectory control other than altitude. Such G&C functions with small engines and in low gravity are challenging, but will largely determine the success of small-body surface-contact missions.

4.1.1.2 Nonlinear Optimization, and Path Planning

Often local trajectory optimization problems require more sophistication than use of linear methods, and onboard nonlinear optimization is required. Methods such as convex optimization can be applied to a wide range of trajectory problems to resolve otherwise intractable onboard problems of path selection. Divert planning to achieve a desired science landing objective is an important example where nonlinear optimization will substantially extend the reach of the divert maneuver. Path-planning algorithms are important where it is important to have the maximum range to search for suitable and safe landing locations.

Status: These algorithms have yet to be applied in flight, and are at relatively low TRL; however, they can be implemented easily, and will likely be necessary for many landing scenarios on the Moon and Mars.

4.1.1.3 Autonomous GN&C Systems

Autonomous onboard GN&C systems have many common aspects that would be applied to the various mission scenarios being described here (see Figure 4-2). Principal among these are an executive control system and GN&C computational components, including sensor data processing, landmark tracking, orbit determination, attitude profiling, attitude estimation, attitude control, and maneuver computation. Retuned and reconfigured through changes in the executive system, these elements can be arranged for multiple tasks in multiple mission scenarios. Part of the executive system responsibility will eventually need to extend to mission planning, when changes in the environment, the status of onboard components, or the forecast trajectory requires changes in the mission plan.

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. Such a system, combined with G&C functions, would provide a completely autonomous GN&C computational capability (e.g., attitude estimation and control). However, it must be noted that this was a relatively primitive system used for a single type of mission—high-speed flybys. Considerable development beyond this state-of-the-art will be necessary to meet future challenges, such as adding automated landmark-based navigation (TRN), linked trajectory guidance and attitude control (6-DOF control), and adaptive filtering for responding to internal and external dynamic events.

4.1.1.4 Integrated GN&C Software Systems, Including 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 radio metrics. 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 fuse IMU and star-tracker data. AutoNav (previous section) fused the data from accelerometers and images. The Orbital Express mission (DARPA) fused optical and laser-ranging data. Future systems will require the use of these data types, and more, including radiometrics obtained from the Earth or from other vehicles.

4.1.1.5 Low-Thrust Guidance

Complete autonomous onboard design of low-thrust trajectories, without any *a priori* design, is probably beyond the scope of near- and mid-term technology; however, onboard invocation of ground-based, nonlinear, low-thrust trajectory design algorithms to re-optimize a current design with altered targeting is well within the reasonable scope of the next decade's missions. Such onboard re-design will be enabling for some low-thrust missions such as a tour of the Galilean satellites, where small deviations from plan can lead to major down-stream penalties without re-optimization.

Status: DS1's AutoNav autonomously corrected the low-thrust trajectory in an iterative non-linear estimation. But a much more complex trajectory, such as a tour of the Jovian moons, would be a much bigger challenge than the deep-space trajectory adjustment approach of DS1.

4.1.1.6 Solar-Sail Guidance and Control

Solar-sail trajectory design shares many characteristics with low-thrust electric propulsion but is far more restrictive. Special adaptations are necessary to the search and convergence tools to make onboard re-optimization of retargeted solar sail trajectories tractable in an onboard environment. However, it is unlikely that solar sails would be used for missions that venture deep into a highly dynamic environment due to their inability to rapidly and generally apply thrust.

Status: No autonomous onboard solar-sail G&C algorithms have flown in deep space.

4.1.2 Target-Relative Estimation

4.1.2.1 Target-Relative Position and Attitude Estimation

TRN is an image processing method that extracts kinematic position (and optionally attitude) information from onboard sensor data (e.g., camera image, LIDAR range image/map, etc.) for subsequent use in an estimation filter. In general, TRN requires the matching of an observed scene against a model. The models can be either actual scaled images of the intended scene or rendered views of 3-D models. Though the raw TRN position (and optionally attitude) information can be of great value, with immediate processing of these providing altitude and rate information, the highest value arises from the use of the raw observed feature or landmark locations in a filter that properly links all of the TRN-processed pictures through accurately modeled dynamics of spacecraft motion.

Status: The Mars Exploration Rover (MER) rovers used a rudimentary form of TRN that determined surface-relative velocity. Though AutoNav on DI did not attempt to understand the terrain of comet Tempel 1, it did adjust the impactor targeting relative to the body in a crude attempt to move the aim point toward the limb autonomously. Many future mission scenarios will need to use an onboard version of the automated landmark tracking being used on the Dawn mission as part of the ground processing.

4.1.2.2 Aeroguidance and Control

The guidance laws of atmospheric entry and guidance are as varied as the methods used to implement such guidance, and in general, specific instantiations will require custom development. However, the underlying framework of a real-time closed-loop GN&C control system will be common, including IMU data filtering, propagation, and executive control. Product lines of aeroguidance subsystems that exploit these commonalities will enhance the economics of missions that require aeroguidance and control techniques.

Status: Mars Science Laboratory (MSL) used the same algorithm for entry of the aeroshell as used by the Apollo capsules, namely center-of-mass adjustments relative to the lift vector via roll maneuvers. Many other techniques for aeroguidance and control are possible, including attack-angle adjustment of a lifting body, drag/lift-tabs, and other drag/lift control, with many variations. All of these new alternatives are relatively low TRL, but many have terrestrial analogs (though generally not at supersonic velocities).

4.1.2.3 Hazard Detection and Avoidance (HDA)

HDA is a landing function that uses data collected on board to identify safe landing sites in real time as the vehicle descends. After detection, the vehicle is diverted to the autonomously selected landing site. Hazard-relative navigation (HRN) though image correlation can be used during the divert and descent to minimize the growth of navigation position errors so that the smallest possible safe haven can be targeted. HDA is most applicable when the proposed landing site has many small hazards that are unavoidable through landing ellipse placement or when the maps are so coarse that landing hazards cannot be identified from orbit.

Status: To date, no landing spacecraft has used HDA. As such subsystems mature, it is almost certain that they will eventually be invoked, especially as landers become more complex and expensive. Such a system was envisioned for Altair, the crewed lunar lander of NASA's cancelled Constellation project.

4.1.2.4 Distributed Spacecraft Cluster Control

Formation flying autonomously coordinates multiple spacecraft to achieve a common goal. The coordination is generally achieved through onboard control of the relative positions and/or attitudes of spacecraft, and so traditional constellations are not considered. NASA applications include (1) two spacecraft for autonomous rendezvous, proximity operations, and docking (ARPOD), which is necessary for on-orbit refueling and satellite servicing (e.g., Hubble), and interferometric synthetic aperture radar (InSAR) (e.g., ESA's TerraSAR-X add-on for Digital Elevation Measurement [TanDEM-X]); (2) several spacecraft for small synthetic apertures (e.g., Terrestrial Planet Finder Interferometer); and (3) tens of spacecraft for large synthetic apertures (e.g., Terrestrial Planet Imager and Stellar Imager). On-orbit assembly, which requires an ARPOD capability, has a variable number of vehicles and is broadly applicable from constructing large, monolithic telescopes to human habitats. Applications of formation flying within PSD are principally in the area of precision formation flying, which requires relative position control to better than approximately 1 cm and/or relative attitude to better than approximately 1 arc-minute. Autonomous GN&C algorithms are needed to maneuver multiple spacecraft in proximity safely (avoiding collisions and light/plume contamination), precisely (meeting requirements for synthesizing an instrument aperture from multiple spacecraft and sensors), reliably (maintaining precision for many years and maintaining safety in fault conditions), and efficiently (without requiring so much fuel, computation, and/or communication as to make missions infeasible).

Swarms, which are loose formations of hundreds to thousands of lower-capability but inexpensively manufactured spacecraft, can be used to synthesize radio frequency apertures and sensor webs to probe planetary magnetic fields or "coat" a comet with sensors, for example. The GN&C algorithms for swarms are fundamentally different from those for precision formation flying due to the scale of the problem and the reduced capability of the individual swarm members. The current state-of-the-art is based on probabilistic approaches, in which high-level swarm behavior emerges from lower-level, simple GN&C algorithms. Quite complex behaviors can be achieved, such as forming an aperture and autonomous self-repair.

Status: Distributed spacecraft control will be demonstrated for the first time on the DARPA F6 mission, which will launch its first element before 2014.

4.1.2.5 Precision-Pointing Systems (Planetary)

In the future, precision pointing is likely to be needed for optical communication links from deep space, and for planetary orbiters with high-resolution optical or SAR imagers, all needing sub-micron class dynamic stability environments and precision tracking of imaging targets. Passive and active approaches at achieving required pointing accuracies call for the development of ultra-stable spacecraft attitude and jitter environments, while calling for additional layers of payload sensing and control—all of this to achieve unprecedented levels of stability, accuracy, and pointing repeatability of a science payload.

Status: Such precision-pointing systems will need to fly with the first optical communications system. Precision pointing for science purposes will likely follow.

4.2 GN&C Flight Instruments

4.2.1 Target-Relative Sensing

4.2.1.1 Altimetry and Velocimetry

LIDAR and RADAR are obvious candidate tools for altimetry, time-of-flight ranging, and velocimetry (e.g., Doppler measurements), but they are not the only choices. Passive or active imaging through the use of visual odometry (stereo picture analysis) or structured light (illumination of the surface with known angular patterns) provides alternative methods when close to the surface or target. Non-stereo passive imaging using TRN image processing can also provide altimetry and velocimetry, if processed through an autonomous navigation filter that accurately models the spacecraft dynamics, or thorough the use of trajectory propagation aided by precision accelerometers.

Status: As mentioned in Section 4.1.2.1, the MER landers used optically based velocimetry. MSL used RADAR-based velocimetry and altimetry in a system that was base-lined for the Altair lunar lander.

4.2.1.2 Terrain Sensors

Terrain sensors can be simple visible or IR imagers that have no range limitation but do require ambient illumination, or active sensors that have range limitations that can operate independent 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. Another distinction may be that instruments intended for terrain sensing also need to function as optical navigation instruments, in which case stars may need to be imaged in the same field as a bright near-field target. An instrument with substantial dynamic range is required in such a case, generally requiring fast optics and high efficiency, deep-well sensor chips.

Status: Cameras have been flying virtually as long as spacecraft have, and virtually any camera can be a terrain sensor. However, for navigation purposes, there are frequently many regimes of operation, often requiring large dynamic range to sense dim signals without undue image smearing. Camera calibration is also an important concern, with continuous read-out video cameras presenting image stability problems that make them challenging for navigation. Many high-precision instruments have successfully combined science and navigation capability, including the Voyagers, Cassini, DS1, DI, Messenger, and ESA's Smart 1.

4.2.1.3 Hazard-Detection Sensor

Flash (and to a lesser extent, scanning) LIDARs are preferred sensors for hazard detection because they provide nearly instantaneous maps of the surface relative to the spacecraft. They provide the best means to assess hazards rapidly. Though at shallow grazing angles, hazards can be difficult to interpret, they can be assessed sufficiently to provide a basis for a terminal descent trajectory.

Status: No dedicated hazard-detection sensors have flown to date.

4.2.1.4 Inter-spacecraft Sensors

Formations and swarms in low-to-middle Earth orbit can leverage GPS. However, direct inter-spacecraft sensors are needed for deep space missions. The direct sensors must also be capable of sensing and distinguishing between multiple spacecraft in a single field of view (FOV) to move beyond ARPOD applications (Table 1 in Scharf et al. 2008 surveys many of the inter-spacecraft sensors available as of late 2007). Generally, payloads will need ultra-precise direct sensors. However, these sensors can be "point-to-point" as they can be placed and oriented based on predetermined formation geometries so that only one spacecraft is in each sensor's FOV. Nonetheless, large-FOV, multi-spacecraft sensors are needed for situational awareness, formation initialization, and collision avoidance.

Status: Radio-based inter-spacecraft sensors will be used for the F6 mission. For more precise metrology, infrared sensors would likely be invoked, but this technology is at lower TRL.

4.2.1.5 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 the G&C algorithms. Much uncertainty exists in the scale heights of planetary atmospheres, but these exert long moment arms on the end trajectory errors. By measuring the air-speed profile and density, adjustments can be made to the trajectory in flight to increase end accuracy.

Status: For accurate guidance into the Martian atmosphere, sensing of atmospheric-relative rates may be used, such as supersonic Pitot tubes; however, such devices are at very low TRL for space applications.

4.2.2 Inertial/Celestial Sensing

4.2.2.1 Nano-g Accelerometers and Precision Gyros

Many GN&C mission scenarios are dominated by IMU errors, including TAG and atmospheric entry through the mapping of *a priori* state errors prior to entry. By using accelerometers that have a precision comparable to the best terrestrial versions, many operations would fundamentally change character from those necessitating continuous navigation updates, to those that can rely for long periods on "dead-reckoning" via IMU. Such a transformation would be especially important for atmospheric entry where there is a critical period in which additional TRN data cannot be obtained. To a large extent, accuracy of acceleration measurements is limited by attitude information, and so precise accelerometry must be met with equivalently precise attitude information from star sensors and gyros.

Status: Current space-application accelerometer technology may be applicable in a very-high precision manner, and so this technology may be a mix of high and low TRLs, but could probably be brought to flight readiness in fairly short order.

4.2.2.2 Precision Time Determination

A number of important mission scenarios and GN&C operations can be dominated by spacecraft clock drift. These include spacecraft-to-spacecraft navigation using one-way radiometrics 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 error 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 risk. 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: Though a new technology, lightweight super-precise clocks are likely to be available within the next five years due to investments by NASA OCT.

4.2.2.3 Milli-arc second Pointing

Though principally required for observatory pointing systems, milli-arc second pointing control will also be required for optical communications. 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. The equipment of interest represents a wide range of precision optical metrology, including micrometer ranging, very-high-precision encoders, and multistage pointing actuation. A three-baseline stellar interferometer concept with short (e.g., 1-meter) to long interferometric baselines brings such components together while offering the potential for sub-milli-arc second class attitude sensing

Status: Such precision pointing systems will need to fly with the first optical communications system. Precision pointing for science purposes will likely follow.

4.2.3 Other GN&C Flight Equipment

4.2.3.1 Microspacecraft GN&C Technology

Micro-spacecraft (e.g., planetary explorers with mass under 100 kg) represent a new opportunity for planetary exploration. The advent of micro electric propulsion systems are largely enabling for this new class of mission. The rapid expansion of CubeSat-class terrestrial missions gives rise to the opportunity to possibly use or adapt some of these inexpensive components for deeper space applications. Such components as momentum control devices, IMUs, and propulsion systems are among those newly available for spacecraft of the order of a few kg, and can be used if proper caution is exercised, as the quality and expected longevity of CubeSat subsystems is not at the level needed for traditional planetary missions. However, the potential exists to invoke some of this microsatellite equipment, at great cost savings, if done carefully, and with thorough investigation and test.

Status: Many components and subsystems are available for CubeSats, and much has flown, but they may be of marginal applicability to planetary missions. Nevertheless, the field is growing rapidly and may prove to be a source of valuable technologies.

4.2.3.2 Radiation-Hardened GN&C Sensors and Avionics

Many recent advances in CPU and sensor electronics and software, most notably for smart phone applications, point to potential beneficial applications to deep space. Interestingly, some smart phone components are surprisingly radiation-tolerant. In other areas, components 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 promise of very robust radiation tolerance, as well as great processor throughput. The path to future missions that will encounter challenging radiation environments (e.g., Europa missions) will likely take advantage of all of these emerging methods.

Status: With increasing attention being paid to the radiation-hardness of commercial aircraft avionics, new approaches and products are appearing in the COTS world that may find their way into planetary missions.

4.2.3.3 Aeroguidance Control Mechanisms

The physical means of controlling vehicles in an atmosphere are varied, and include center-of-mass adjustment, aeroshell attack-angle adjustment, or adjustments of the aeroshell itself, through drag tabs and other means. Further, 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: MSL used the same algorithm for entry of the aeroshell as used by the Apollo capsules, namely center-of-mass adjustments, relative to drag vector by roll maneuver. 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. All of these new alternatives are at relatively low TRL, but many have terrestrial analogs (though generally not at supersonic velocities).

4.2.3.4 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 none 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.

4.2.4 GN&C Ground Test Facilities

4.2.4.1 Free-Flying Propulsive Test Platforms (Short-Duration)

Some highly time-critical and high-propulsion events can be adequately tested only in realistic simulation. EDL is a notable case, 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 prove 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 were used for the Apollo lunar program, and are beginning to be used again to test complex GN&C and other systems.

4.2.4.2 Laboratory 6-DOF Emulators

Relatively low-speed GN&C operations can be tested in real time and real scale, or even scaled 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 GN&C scenarios.

4.2.4.3 Aerial GN&C Test Platforms (Long-Duration)

GN&C and operations scenarios of long duration can best and most economically be emulated in aircraft flight-tests, most especially helicopters and UAVs. Such tests are highly conducive to terrain traverses that require landmark-based autonomous navigation with TRN, especially of different scaling regimes—allowing the aircraft 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, with an aircraft providing nothing like the acceleration profile expected during a space operation; thus control laws cannot be properly tested. 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 hours.

Status: Fully autonomous UAVs offer increasingly economical means of testing navigation, and in some limited instants, G&C algorithms and systems. Able to cover long-distance terrain over long time spans, UAVs will make testing of lunar landing, and small-body TAG and orbit scenarios possible in a long-scenario fully closed-loop manner.

4.2.4.4 High-Speed EDL Test Platform

A very specialized but critical platform will be a hypersonic test rig for the proving of atmospheric entry components such as chutes, drag devices, and lifting bodies. Deployed from aircraft or from suborbital flights, such relatively expensive platforms will be invaluable to reduce risk for these critical entry elements, but still at cost well below that of suborbital test flights.

Status: OCT is currently fielding such a test effort for a high-speed Mars entry hypersonic chute on a suborbital flight; this demonstration, though not a generic platform, will provide much-needed advancement of this technology. A generic multi-mission, supersonic test rig is lacking, but would contribute in a number of areas especially for Mars landing technology development.

5 Onboard GN&C Technology with Respect to Future Planetary Science Missions

In Appendix B, GN&C technologies are mapped to the GN&C capabilities needed for each of the recommended missions from the 2011 Planetary Science Decadal Survey and studies. Table B-1 correlates these technologies with those missions. For each mission and technology, a correlation color-grade is assigned, qualitatively assessing as low, medium, or high (green, yellow, or red) the relevance of that technology to the mission; these color grades are then summed by column. Also, TRL and relative cost factors are assigned to each of the technologies that will lead to quantitative assessment of need vs. cost factors.

Table 5-1 provides results of the analysis summarized in Table B-1; a discussion follows.

Table 5-1. Results of technology assessment for missions recommended in the 2011 Planetary Science Decadal Survey (prioritization by frequency of potential use, and by frequency amplified by cost and technical maturity).

Raw Prioritization / Cost-Moderated Prioritization	Highest Priority	High Priority
Highest Priority	6-DOF G&C, nonlinear path planning, integrated GN&C s/w systems, target-relative position and attitude estimation, nano-g accelerometers, advanced onboard computation	Low-thrust guidance, terrain sensors
High Priority	Aerial platform GN&C emulators	Microspacecraft GN&C technology, precision planetary pointing systems, altimetry and velocimetry, hazard-detection sensors, free-flying propulsive platforms, laboratory 6-DOF emulators

5.1 Leading Onboard GN&C Technology Investment Needs of Missions Recommended in the Planetary Science Decadal Survey

Table B-1 performs two types of analyses. These analyses ignore the likelihood or frequency of possible missions, and only note the placement of mission possibilities in the Planetary Science Decadal Survey. In the subsequent cost analysis, the overall mission cost is also ignored; only the cost and maturity of the technology is noted in a qualitative sense. The first analysis is a simple summing of priority by technology type, but against recommended specific missions in the Decadal Survey:

High-Scoring GN&C Technologies, Based Solely on Mission Need

- 6-DOF G&C
- Nonlinear optimization and path planning
- Autonomous GN&C systems
- Integrated GN&C software systems, including multisource data fusion
- Target-relative position and attitude estimation
- Nano-g accelerometers
- Micro-spacecraft GN&C technology
- Advanced onboard computation

Medium-Scoring GN&C Technologies, Based Solely on Mission Need

- Low-thrust guidance
- Precision pointing systems (planetary)
- Altimetry and velocimetry
- Terrain sensors
- Hazard-detection sensors
- Atmospheric-relative sensing
- Free-flying propulsive test platforms (short-duration)
- Laboratory 6-DOF emulators
- Aerial GN&C test platforms (long-duration)

A further analysis can be applied to these results. By scaling them to relative system development and deployment cost, and inversely by TRL, we can achieve a relative cost-qualified prioritization. In this case, a comparison to the raw scoring listed above to the cost-qualified scaling will reveal whether the need (i.e., mission "pull") is proportional or disproportional to the investment cost. Though a disproportional rating (on the costly side) would not and should not disqualify a technology investment, it might spur investigation into alternative, less costly technologies, or alternative mission scenarios. Alternatively, disproportionality on the cost-advantage side would imply a good target for investment that would lead to better and potentially cheaper planetary missions:

High-Scoring GN&C Technologies, with Mission Need Qualified by Cost and TRL

- 6-DOF G&C
- Nonlinear optimization and path planning
- Autonomous GN&C systems
- Integrated GN&C software systems, including multisource data fusion
- Low-thrust guidance
- Target-relative position and attitude estimation
- Terrain sensors
- Nano-g accelerometers
- Advanced onboard computation
- Aerial platform GN&C emulators (long-duration)

Medium-Scoring GN&C Technologies, with Mission Need Qualified by Cost and TRL

- Solar sail G&C
- Precision pointing systems (planetary)
- Altimetry and velocimetry
- Hazard-detection sensors
- Micro-spacecraft GN&C technology
- Radiation-hardened GN&C sensors and avionics
- Free-flying propulsive test platforms (short-duration)
- Laboratory 6-DOF emulators
- Aerial platform GN&C emulators (long-duration)
- Laboratory 6-DOF emulators

In summary, advancement in autonomous GN&C capability, the ability to autonomously manipulate spacecraft trajectory and attitude autonomously 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 be necessary. In situations with tight time constraints (e.g., EDL onto a surface with significant gravity) and high dynamics, increasingly integrated control of the trajectory and attitude of the spacecraft will become necessary, as opposed to the traditional approach of controlling the trajectory and attitude separately. Overall system and software executive technology to enable autonomous execution of the onboard autonomous GN&C functions is necessary. 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.

6 Technology Development Roadmap

Table 6-1 synthesizes the analysis from Appendices B and C into a roadmap of GN&C technology use vs. time. In this table, each of the possible uses of these technologies is tallied, as either necessary or contributing components, for a particular mission displayed by year and summed for that year in a histogram. In this fashion, each technology can be assessed by the number of possible use-cases over time. It should be noted that each of these mission concepts has varied paths to implementation, from simple to complex. Missions increase in complexity for one of two reasons, to obtain more and better science or to reduce risk. For the purpose of Table 6-1, the higher end of the complexity scale is assumed to assign “necessary” status to a particular mission. This is not to say that simpler, less costly, less ambitious versions of these missions could not be mounted at some increased risk and reduced science return. For either a “necessary” or “contributing” category, Table 6-1 shows when the specific technology will be needed by a particular mission. Clearly, development of that technology will be required some years in advance of the need.

Table 6-1. GN&C technology and mission use timeline and roadmap.

Prospective Mission	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
	Mission Operations Phase														
NEO Surveyor/Explorer					■	■	■	■	■	■					
Europa Orbiter						■	■	■	■	■	■	■	■	■	■
Comet Sample Return						■	■	■	■	■	■	■	■	■	■
Venus in Situ Explorer						■	■	■	■	■	■	■			
Aitken Basin Sample Return						■									
Planetary Defense Precursor							■	■	■	■	■				
MSR								■	■	■	■				
Mars Netlander									■	■					
Europa Lander											■	■	■	■	■
Uranus Orbiter & Probe												■	■	■	■
Io Observer												■	■	■	■
Lunar GEO Network												■			
Titan and Saturn Probe												■	■	■	■
Trojan Tour												■	■	■	■

GN&C Technology Element		2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
		Accumulated use count per year of each GN&C Technology Element														
GN&C Flight Algorithms and S/W																
1. 6-DOF guidance and control	Necessary				2		3				6				7	
	Enhancing							1		2	4				6	
2. Non-linear optimization, and path planning	Necessary				2		3			4	5				6	
	Enhancing							1		2	5				7	
3. Autonomous guidance navigation and control systems	Necessary			1	3	4				6	7					
	Enhancing				1			2			4				7	
4. Integrated GN&C software systems including multi-source data fusion	Necessary			1	3	4	5			6	7					
	Enhancing				1			2			4				5	
5. Low-thrust guidance	Necessary			1							4					
	Enhancing							2		3	4				5	
6. Solar sail guidance and control	Necessary															
	Enhancing			1		2					4				5	
7. Target-relative position and attitude estimation	Necessary				1		2				6				10	
	Enhancing				1			2			3					
8. Aeroguidance and control	Necessary						2									
	Enhancing				1			2			3					
9. Hazard detection avoidance	Necessary						2								3	
	Enhancing										2					
10. Distributed spacecraft cluster control	Necessary															
	Enhancing							1								
11. Precision pointing systems (planetary)	Necessary															
	Enhancing									2	3				4	
GN&C Flight Instruments																
12. Altimetry and velocimetry	Necessary						1			2						
	Enhancing					1		2			4					
13. Terrain sensors	Necessary			1	2	3	4			5						
	Enhancing							1			3					
14. Hazard detection sensors	Necessary				2					3	4					
	Enhancing			1	2	3					4					
15. Inter S/C sensors	Necessary															
	Enhancing									1						
16. Atmospheric relative sensing	Necessary						1									
	Enhancing										1				2	
17. Nano-g accelerometers	Necessary			1	2	3	4			5						
	Enhancing				2					3	4				5	
18. Precision time determination	Necessary															
	Enhancing			1	2	3	4									
19. Mili-arc-second pointing	Necessary															
	Enhancing															
Other GN&C Flight Gear																
20. Microspacecraft GN&C technology	Necessary			1	2						3					
	Enhancing							2								
21. Radiation-hardened GN&C sensors and avionics	Necessary									1	2					
	Enhancing				3	4	5	6			10					
22. Aeroguidance control mechanisms	Necessary						1									
	Enhancing				1											
23. Solar sail control mechanisms	Necessary															
	Enhancing			1		2					4				5	
24. Advanced onboard computation	Necessary			1	2						3					
	Enhancing				3	4				6	9				10	
GN&C Ground Test Facilities																
25. Free-flying propulsive test platforms (short-duration)	Necessary				1										3	
	Enhancing				2						4					
26. Laboratory 6-DOF emulators	Necessary						1	2	3	4	5					
	Enhancing														2	
27. Free-flying UAV-based test platforms (long-duration)	Necessary				1		2	3	4	6	7				8	
	Enhancing							1			3					
28. High-speed EDL test-platform	Necessary							2			3					
	Enhancing							1			2					

Key: Necessary Technology   Enhancing Technology

7 Findings and Recommendations

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 broadly required for next-generation SMD PSD missions aimed to reach and explore scientific targets with unprecedented accuracies and proximities (Section 4.1.1).

Recommendation: Invest in 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.

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 such as LIDARs and spaceflight-qualifiable computing elements for enhanced on-instrument analysis ability (Section 4.2).

Recommendation: Invest in 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. For example, a camera, a LIDAR, an inertial measurement unit (IMU), and a computer can constitute an integrated sensor system that provides altimetry, velocimetry, target-relative navigation, and hazard detection—one sensor system replacing four sensor systems.

Finding 3

New and advanced GN&C algorithms: Advanced algorithms in guidance, estimation, and control are needed in parallel with advancements in hardware, software, and architecture (Section 4.1).

Recommendation: Invest in 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. Algorithms must be developed in parallel with new architectures, hardware, and software.

Finding 4

Onboard GN&C is performed by systems and not just components. As more complex systems with stringent performance requirements are pursued, the interplay across components, flight dynamics, and physical environment increases. System-level physical test and demonstration systems are necessary (Sections 4.1.1.4, 4.2.4).

Recommendation: Invest in system-level demonstration systems, such as end-to-end GN&C system testbeds, aerial field tests, sounding rockets tests, and free-flying-vehicle-based, closed-loop GN&C system tests.

Finding 5

Testing capabilities are critical and need to be improved. End-to-end system-level modeling, testing, and simulation are required to flight-qualify newly developed system-level capabilities achieved through incorporation of new technology elements (Section 4.2.4).

Recommendation: Continue to advance integrated modeling and simulation at the mission capability level, with increasing fidelity matching advancements in component technologies.

Finding 6

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. SMD provide incentives in the structure of announcements of opportunity such that feed-forward of developments for one project to the next can be maximized.

Finding 7

General onboard 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 (Section 4.1.1.3).

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 workshops where NASA GN&C technologists would invite leading technologists in other fields to explore technology-transfer opportunities.

Finding 8

GN&C commonality across NASA: There is much to be learned by the human spaceflight program from GN&C experience in SMD. Though the scales are vastly different, the methods and technologies are the same. Although crewed missions were not specifically part of the analysis reported here, it became evident upon completion of the analysis that many planetary mission GN&C technology needs mirror those of the first envisioned exo-Earth/Moon human missions. For this reason, there should be substantial opportunities for SMD and the Human Exploration and Operations Mission Directorate (HEOMD) to cooperate on mutually beneficial GN&C technology and subsystem development.

Recommendation: Assign a task to the NASA Engineering and Safety Center GN&C Working Group/Community of Practice to identify cross-cutting GN&C technologies across the human and robotic exploration programs, and propose strategies for common development. Such a catalog and strategy should inform future technology plans for both the human and robotic programs and will be of substantial benefit to NASA.

Appendix A. Missions from the 2011 Decadal Survey and Major Concept Studies

This appendix provides GN&C-centric descriptions of the missions denoted in the 2011 Planetary Science Decadal Survey, and indications of how advanced GN&C technology development needs correlate.

A.1 Flagship Mission Recommendations

A.1.1 Mars Sample Return

There are five presumed principal segments of the MSR mission: (1) EDL, (2) roving/sample gathering and caching, (3) ascent and orbit, (4) orbital capture and transfer, and (5) return to Earth. Of these five segments, 1 and 4 contain substantial pulls for new onboard GN&C technology. To obtain maximum scientific value from the samples, a maximally accurate landing of the sampling spacecraft will be necessary, with pinpoint accuracy (a few meters)—possibly obviating the need for a complex rover entirely. To provide such accuracy, precise aeroguidance capability will be required, including control of the aero-characteristics of the vehicle, and atmosphere-relative measurements. High-precision accelerometers may also serve well to increase landing accuracy at relatively low cost. Alternatively, a high-capability rover may be used to reduce the need to precisely target a surface region for sampling. Phase 4 will necessitate autonomous onboard rendezvous and capture of the lofted sample canister. Such a capture system will be essentially a generic AR&D system. Advanced GN&C-specific imagers, and integrated GN&C instruments and software will provide cost savings for this and other missions.

A.1.2 Jupiter Europa Orbiter

A Jupiter Europa orbiter mission will combine the characteristics of a hazardous environment mission (radiation) and a small, primitive-body mission (requiring TRN). Additionally, this mission may lower launch mass and cost by using low-thrust propulsion to reach Jupiter and enter the Jovian system. Depending on the architecture, the radiation protection will likely require special hardness of key electronics such as the CPU. Additionally, the optical sensors (for TRN) will need to be especially radiation-resistant to cope with the Jovian radiation field. Because of the long light times, much autonomous onboard navigation capability will be necessary to take maximum advantage of close satellite flyby opportunities. Advanced GN&C-specific imagers and integrated GN&C instruments and software will provide cost savings for this and other missions; however, some low-cost versions of this mission (e.g., Europa Clipper) use a Europa-synchronous orbit around Jupiter to reduce the number and criticality of the satellite flybys, and as such, may be able to forgo much automation with minimal propellant mass penalty.

A.1.3 Uranus Orbiter and Probe

Like a Jupiter Europa orbiter, the Uranus orbiter will use TRN in the moon system. Onboard navigation autonomy is even more imperative for this mission due to the very long round-trip light-times. The radiation environment for this mission will be much less severe than for a Jupiter-Europa mission. Navigation (as well as science) imagers may be substantially different as well, with the much lower light levels, requiring bigger aperture lenses to capture the same signal level as at, say, Jupiter. The latter is necessary because the relative orbital velocities are similar, and image smear is a concern both for imaging navigation and for science.

A.2 New-Frontiers-4 Recommendations

A.2.1 Comet Surface Sample Return

Comet surface sample return missions are the first of what will be several missions in this section that are small, primitive body explorers. Samplers will require TAG technology, a type of AR&D GN&C system that can make close, controlled approaches and gentle contact with the rotating surface of the body. These missions will also require TRN and imagers for TRN as well as a means of independent altitude measurement (other than the imaging) to provide a very high degree of mission safety. 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 provide for very accurate contact operations without substantial system complexity. Some projectile and harpoon approaches to sample return require precision spacecraft maneuvers and autonomous rendezvous and capture.

A.2.2 Lunar South Pole–Aitken Basin Sample Return

A soft landing on the Moon, probably in rugged terrain to ensure a sampling of deeply excavated core material will require several high-technology GN&C elements. These include TRN (landmark modeling and tracking), autonomous onboard navigation and control (for precise targeting and landing), and general automation capability, to provide high levels of mission assurance for landed operations and ascent especially for mission scenarios that take place on the far side of the Moon. And for such missions, further autonomous guidance will be required for the ascent and return to Earth, perhaps even requiring automated path planning and optimization. High precision accelerometers may also serve to increase landing accuracy at relatively low cost.

A.2.3 Titan and Saturn System Mission (and Probe)

A Titan and Saturn System mission (and probes) will require modest amounts of advanced GN&C technology, unless (which is unlikely) a very precise targeting of the probe is required. Onboard autonomy may be desired to reduce operations costs by allowing the spacecraft to perform many routine operations itself. In addition, such advanced autonomy would be advisable to have a robust fault protection system that can strive to “fail operational” for many soft faults. Automated science planning and execution for the carrier vehicle—likely present—will allow for reactive science image targeting based on current navigation solutions; such systems require advanced GN&C capability.

A.2.4 Trojan Asteroid Tour and Rendezvous

Such a mission will require the full range of small-body GN&C capability, including autonomous low-thrust operation, surface operations such as TAG, TRN, and automated science mapping. 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.

A.2.5 *Venus* in Situ *Explorer*

A Venus lander mission will require substantial automated GN&C systems, the most important of them being EDL. Many portions (and the most interesting portions) of the planet's surface are rugged; entry G&C will be necessary to navigate to such regions, and HDA necessary to ensure a safe landing. A relay orbiter could provide onboard automation for orbit maintenance, lander pointing, and other otherwise laborious but automatable operations. Maintenance of trajectory control in the presence of wind is necessary during EDL. This may mean the need to develop a steerable parachute to be used during the long slow descent.

A.3 New-Frontiers-5 Recommendations: NF-4 plus…

A.3.1 *Io Observer*

The paramount GN&C technology requirement for an Io observer mission will be for radiation-hardened GN&C equipment. An Io orbiter would probably use electric propulsion to achieve an Io orbit using multiple swing-bys of the other Galilean satellites. The timing and targeting of such gravity assists is crucial, as is the post-close-approach retuning of the trajectory. Cleanup maneuvers within an hour of the flyby may be required, virtually eliminating a ground-based operation. Onboard navigation and guidance computations will likely be required, as will nonlinear optimization of the path, in order to conserve propellant. For accurate navigation, TRN will be required throughout the tour and the orbital phase. Advanced GN&C-specific imagers, and integrated GN&C instruments and software, will provide cost savings for this and other missions.

A.3.2 *Lunar Geophysical Network*

The GN&C-specific needs of this mission will be largely determined by the needed precision of the landing sites of the network nodes. If high precision is needed, autonomous navigation and guidance will be required, in turn requiring TRN. Some landing regions will most likely be hazardous, requiring hazard avoidance systems. Altimeters may be required, as well as imagers (potentially IR). Integrated GN&C instruments and computation systems may save costs for a network of such landers.

A.4 Other Missions

A.4.1 *Europa Lander*

A Europa lander mission will share many characteristics with other large-gravity (but non-atmosphere) landers, such as for the Moon, potentially including the requirements for TRN, automated onboard GN&C-driven EDL, imagers, HDA, and an altimeter. But as with any Jovian mission, the severe radiation environment of that system will be a dominant driver of GN&C systems. And, as with other Jovian explorers discussed, this will likely be an electric propulsion mission, and use multiple swing-bys of the outer Galilean satellites to achieve a Europa orbit resonance; as such, TRN, HDA, and autonomous onboard navigation and guidance will be required to meet the need for rapid trajectory updates and possible path re-optimizations immediately following swing-bys.

A.4.2 NEO Surveyor/Explorer

The NEO surveyor/explorer class of missions would investigate NEOs for general planetary science purposes, planetary defense purposes, and pre-mission surveys and reconnaissance for human exploration. These missions share characteristics of other small-body missions, including the Trojan asteroid tour, and comet surface sample return, including the need for autonomous onboard GN&C, TRN, imagers, precision accelerometers, and altimeters. If surface contact is going to be made, precision TAG subsystems will be required. Integrated GN&C instruments and computation systems may save costs for a network of such landers.

A.4.3 Planetary Defense Precursor

There could eventually be missions to scope possibilities for planetary defense. These may be small investigatory surveyors to assess physical characteristics and leave precision-clock-based radio beacons, technology demonstrations for mitigation, such as electric propulsion systems, or actual test-deflections, using schemes such as gravity tractors. Such missions might include actual retrieval of a small asteroid bringing it to a human-reachable station, such as an E/M L2 point. Such missions will share all of the GN&C new technology needs of other small missions discussed above, including autonomous onboard GN&C—including TAG systems, TRN, instruments, and altimeters. Some of these missions that apply propulsion to a target may require special targeting ability and thrust planning to effectively cause a deflection. A gravity tractor (use of a large-mass spacecraft, e.g., 2000 kg, to provide a very small but discernible force over a long time period) will require formation-flying subsystems combined with natural-body precision tracking.

A.4.4 Mars NetLander

Like the lunar network missions, the Mars networks may require targeting landing. Depending upon the risk posture assumed for the mission, hazard avoidance systems may be required. As with previous landers discussed, onboard autonomous GN&C equipped with TRN will be required for precision landing. Altimeters may be required, as well as imagers (potentially IR). Integrated GN&C instruments and computation systems may also save costs for a network of such missions.

Appendix B. Tabular Analysis of Onboard GN&C Technology with Respect to Future Planetary Science Missions

In this appendix, GN&C technologies are mapped to GN&C capabilities needed for each of the recommended missions from the 2011 Planetary Science Decadal Survey and studies. Table B-1 correlates these technologies with those missions. For each mission and technology, a correlation value is assigned, qualitatively assessing as low, medium, or high the relevance of that technology to the mission, and values of 0, 5, and 10 assigned respectively for purposes of quantitative assessments. Also, TRL and relative cost factors are assigned to each of the technologies that will lead to quantitative assessment of need vs. cost factors. These results are used to obtain the qualitative ranking discussed in Section 5.

Table B-1. Onboard GN&C technologies vs. Decadal Survey recommended missions, and onboard GN&C technology needs.

						Specific Missions from Decadal Survey (DS)											Large (Planetary) Missions from DS			Other Large Missions			Other Missions							
						#1 Mars Sample Return				NF 4 Suggestions from DS					NF 5 Suggestions (NF 4 plus...)															
	Specific GN&C Technologies	Relative Cost Factor	TRL	Technology Examples	Necessary Mission Technology Dependence*	Entry Phase	Rover Phase	Orbit, Rendezvous, Docking Phase	Earth Entry Phase	Comet Surface Sample Return	Lunar South Pole-Aitken Basin Sample Return	Saturn Probe	Trojan Asteroid Tour and Rendezvous	Venus In Situ Explorer	Io Observer	Lunar Geophysical Network	Titan Saturn System Mission (and Probe)	Jupiter Europa Orbiter	Uranus Orbiter and Probe	Europa Orbiter	Neptune Orbiter and Probe	Ganymede Orbiter	Europa Lander	NEO Surveyor Explorer	Planetary Defense Precursor	MicroNEO Explorer	Mars Geophysical Network	Raw Totals (Mission Need)	Cost Totals (Cost Factor *1000/Need)	Investment Cost - Benefit Priority Score (TRL/Cost Total)
	GN&C Flight Algorithms and S/W					A	B	C	D	E	F	G	H	I	J	K	G	L	M	M1	N	O	O1	P	Q	R	S			
Inertial Onboard GN&C	6-DOF guidance and control	0.2	5	Touch and go ascent guidance; large vehicle descent guidance and control, pinpoint landing with large diverts, AR&D	A, E, F, I, Q, R, O1																									
	Non-linear optimization, and path planning	0.2	3	Optimal path planning for small body ProxOps, high-gravity precision landing, EDL	A, F, I, Q, R, O1																									
	Autonomous GN&C systems	0.3	5	Multi-use, multi-mission GN&C systems, integrated GN&C and mission/science planning	B, C, E, H, L, M, M1, O, P, Q, R, O1																									
	Integrated GN&C s/w systems (including multi-source data fusion)	0.3	4	Autonomous onboard GN&C, data fusion (e.g., LIDAR/altimeter/ velocimeter plus TRN)	C, E, H, L, M, M1, O, P, Q, R, O1																									
	Low-thrust guidance	0.3	6	Low-trust trajectory design and control, small body, station keeping and PROXOPS, AR&D	L, M, O1																									
	Solar sail guidance and control	0.3	4	Trajectory design and control methods specifically for solar sail low-thrust missions	—																									
Target-Relative Estimation	Target-relative position and attitude estimation	0.3	5	Target-Relative-Navigation (TRN), image processing, pose estimation (for AR&D), landmark and feature tracking	C, E, F, H, J, O1, M1, O, P, Q, R																									
	Aeroguidance and control	0.4	2	Atmospheric entry guidance, including aerobraking, CM control, control surfaces, and chute control	A																									
	Hazard detection avoidance	0.4	3	Landing systems for Moon and Mars; some small/primitive body landing systems	A, I, O1																									
	Distributed s/c cluster control	0.4	2	Constellation and swarm path computation and element guidance	—																									
	Precision pointing systems (planetary)	0.3	5	Optical com pointing, distributed s/c systems, surface target pointing	—																									

						Specific Missions from Decadal Survey (DS)											Large (Planetary) Missions from DS			Other Large Missions			Other Missions							
						#1 Mars Sample Return				NF 4 Suggestions from DS					NF 5 Suggestions (NF 4 plus...)															
	Specific GN&C Technologies	Relative Cost Factor	TRL	Technology Examples	Necessary Mission Technology Dependence*	Entry Phase	Rover Phase	Orbit, Rendezvous, Docking Phase	Earth Entry Phase	Comet Surface Sample Return	Lunar South Pole-Aitken Basin Sample Return	Saturn Probe	Trojan Asteroid Tour and Rendezvous	Venus In Situ Explorer	Io Observer	Lunar Geophysical Network	Titan Saturn System Mission (and Probe)	Jupiter Europa Orbiter	Uranus Orbiter and Probe	Europa Orbiter	Neptune Orbiter and Probe	Ganymede Orbiter	Europa Lander	NEO Surveyor Explorer	Planetary Defense Precursor	MicroNEO Explorer	Mars Geophysical Network	Raw Totals (Mission Need)	Cost Totals (Cost Factor *1000/Need)	Investment Cost - Benefit Priority Score (TRL/Cost Total)
	GN&C Flight Instruments					A	B	C	D	E	F	G	H	I	J	K	G	L	M	M1	N	O	O1	P	Q	R	S			
Target-Relative Sensing	Altimetry and velocimetry	0.7	7	LIDAR and RADAR based altimetry and velocimetry, visual odometry, structured light proximity sensor	A, E, F, H, I, O1, P, Q, R, S																									
	Terrain sensors	0.6	7	Imagers for landmark and feature tracking, combined science and GN&C sensors, wide and narrow angle	A, E, F, H, I, O1, M1, O, P, Q, R, S																									
	Hazard detection sensors	0.6	6	Scanning and flash LIDARS for all seeing conditions, other active optical sensing	E, F, H, P																									
	Inter s/c sensors	0.6	7	Formation flying, s/c clusters, etc., sensors for range, and/or bearing	—																									
	Atmospheric relative sensing	0.6	4	Air speed gauges, pressure sensors, drag estimation	A, I, S																									
Inertial/Celestial Sensing	Nano-g accelerometers	0.3	5	Accelerometers for EDL, aerobraking, crewed missions, TAG	A, E, F, H, P, Q, R																									
	Precision time determination	0.5	5	Space clocks with time as good as DSN; ship-to-ship nav, orbital event sequencing, one-way radiometrics, NEO beacon, time distribution & sync	P, Q, R																									
	Milliarcsecond pointing	0.5	4	Precision metrology and encoders, ranging and multi-stage actuation	—																									
	Other GN&C Flight Gear																													
	Micro-spacecraft GN&C technology	0.6	6	Micromomentum wheels, gyros and propulsion, including micro EP	H, I, R																									
	Radiation-hardened GN&C sensors and avionics	0.6	5	Rad-resistant CPUs, imagers, gyros MEMs accels	J, L, M1, O,																									
	Aero-guidance control mechanisms	0.5	3	Control mechanisms for atmosphere entry vehicles and/or exo-Earth aircraft	A, I																									
	Solar sail control mechanisms	0.5	2	Control mechanisms for solar sails, including shape control, control tabs, and spin control	—																									
	Advanced onboard computation	0.4	5	High performance and rad-hard (by design or by s/w) CPUs; including multi-core, and fast-conventional	E, H, P, R																									

					Specific Missions from Decadal Survey (DS)											Large (Planetary) Missions from DS			Other Large Missions			Other Missions							
					#1 Mars Sample Return				NF 4 Suggestions from DS					NF 5 Suggestions (NF 4 plus...)															
Specific GN&C Technologies	Relative Cost Factor	TRL	Technology Examples	Necessary Mission Technology Dependence*	Entry Phase	Rover Phase	Orbit, Rendezvous, Docking Phase	Earth Entry Phase	Comet Surface Sample Return	Lunar South Pole-Aitken Basin Sample Return	Saturn Probe	Trojan Asteroid Tour and Rendezvous	Venus In Situ Explorer	Io Observer	Lunar Geophysical Network	Titan Saturn System Mission (and Probe)	Jupiter Europa Orbiter	Uranus Orbiter and Probe	Europa Orbiter	Neptune Orbiter and Probe	Ganymede Orbiter	Europa Lander	NEO Surveyor Explorer	Planetary Defense Precursor	MicroNEO Explorer	Mars Geophysical Network	Raw Totals (Mission Need)	Cost Totals (Cost Factor *1000/Need)	Investment Cost - Benefit Priority Score (TRL/Cost Total)
GN&C Ground Test Facilities					A	B	C	D	E	F	G	H	I	J	K	G	L	M	M1	N	O	O1	P	Q	R	S			
Free-flying propulsive test platforms (short-duration)	1	5	Rocket/jet-powered platform for short-duration EDL, hazard avoidance, and other terminal descent tests	A, I																									
Lab 6-DOF emulators	0.8	7	Air tables/floors, robotic arms/platforms for simulating proximity operations to objects and vehicles	C, E, F, H, O1, Q, R																									
Aerial platform GN&C emulators (long-duration)	0.6	7	Aircraft-based test platform for testing long-period GN&C scenarios, including crewed helicopters and UAVs	C, E, H, I, L, M1, O, O1, P, Q, R, S																									
High-speed EDL test-platform	1	4	Hypersonic test platform (aircraft carried) for test of EDL systems, including lifting bodies and chutes	A, G, I, M1, O, N, S																									
				TOTALS																									

*Critical Msn Technology Development Key

Specific Missions from Decadal Survey (DS)

#1 Mars Sample Return

A = Entry phase
B = Rover phase
C = Orbit, rendezvous, docking phase
D = Earth entry phase

NF 4 Suggestions from Decadal Survey

E = Comet Surface Sample Return
F = Lunar South Pole-Aitken Basin Sample Return
G = Titan Saturn System Mission (and Probe)
H = Trojan Asteroid Tour and Rendezvous
I = Venus In Situ Explorer

NF 5 Suggestions (NF 4, plus…)

J = Io Observer
K = Lunar Geophysical Network

Large (Planetary) Missions from DS

L = Jupiter Europa Orbiter
M = Uranus Orbiter and Probe

Other Large Missions

M1 = Europa Orbiter
N = Neptune Orbiter and Probe
O = Ganymede Orbiter

Other Missions

O1 = Europa Lander
P = NEO Surveyor Explorer
Q = Planetary Defense Precursor
R = MicroNEO Explorer
S = Mars Geophysical Network

***Relevance Level Key*

Low Medium High

Appendix C. Timeline and GN&C Technology Use-Frequency Timeline by Decadal Survey Mission

The analysis in this appendix builds upon the detailed mission-by-mission GN&C technology use data from Appendix B, and lays out that information in a time-ordered fashion. Table C-1 represents a transcription of Table B-1 in this time-ordered fashion, showing all potential GN&C technology uses as both "necessary" and "contributing" technology elements (corresponding to red and yellow correlation grades in Table B-1). The results of Appendix C are presented, technology by technology, in Section 6, where for each, the number of possible uses of these technologies, as either necessary or contributing components, is displayed by year. In this fashion, each technology can be assessed by the number of possible use-cases over time.

Table C-1 correlates the technologies that form the columns of Table B-1, which are numbered consecutively as follows:

GN&C Flight Algorithms and S/W

1. 6-DOF G&C
2. Nonlinear optimization, and path planning
3. Autonomous GN&C systems
4. Integrated GN&C software systems including multisource data fusion
5. Low-thrust guidance
6. Solar sail G&C
7. Target-relative position and attitude estimation
8. Aeroguidance and control
9. HDA
10. Distributed spacecraft cluster control
11. Precision pointing systems (planetary)

GN&C Flight Instruments

12. Altimetry and velocimetry
13. Terrain sensors
14. Hazard-detection sensors
15. Inter-spacecraft sensors
16. Atmospheric-relative sensing
17. Nano-g accelerometers
18. Precision time determination
19. Milli-arc second pointing

Other GN&C Flight Gear

20. Micro-spacecraft GN&C technology
21. Radiation-hardened GN&C sensors and avionics
22. Aeroguidance control mechanisms
23. Solar-sail control mechanisms
24. Advanced onboard computation

GN&C Ground Test Facilities

25. Free-flying propulsive test platforms (short-duration)
26. Laboratory 6-DOF emulators
27. Aerial GN&C test platforms (long-duration)
28. High-speed EDL test-platform

For each mission, the necessary and enhancing GN&C technologies are listed, as well as the time when they would be required to be at the necessary TRL to be integrated into the mission—which in the case of hardware is assumed to be two years before launch. For software subsystems that are required for encounter operations, these can appear on the mission timeline well after launch, and be uploaded to the spacecraft. At the bottom of the chart, these use tallies are added for each of the technologies (1 through 28) as either necessary or enhancing as a sum across the timeline. This sum gives a measure of the relative need of these elements over time and overall. These sums appear in matrices according to their position in the matrix for each of the 28 technologies listed above.

It is important to note that there is no single detailed technical description or concept for any of these missions; rather, they are mission concepts noted (by and large) in the Decadal Survey. For the purposes of this chart, as with all of the tables, the missions were interpreted to be broader and more aggressive in scope rather than narrower and more modest, to capture a better GN&C perspective across missions and programs. It is certainly true that a variety of methods can be applied to accomplish any given mission, some invoking more elaborate GN&C strategies, and others not, but in all cases the greater the GN&C sophistication is always invested for the purpose of greater science return through more ambitious mission objectives.

Also, it should be noted that, as discussed, the various GN&C technologies are at varying TRLs, implying that missions choosing a particular GN&C capability will have varying requirements for readying different elements. In some cases, where the subsystem is at particularly low TRL, substantial development is required; in others, tests and flight certification may be the only necessary project investment. In many cases, closely related technology elements can be adapted across categories, again highlighting the benefits of being aware of GN&C technologies as elements of a broad system that can and should be viewed holistically.

Table C-1. Onboard GN&C technology timeline.

Mission	Launch	Necessary Technologies	Enhancing Technologies	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
NEO Surveyor/ Explorer	2017	1,2,3,4,5,7,13, 17,20,24,26,27	6,9,14,18,21, 23,25			3,4,5,13, 17,20,24, 6,14,18, 21,23				1,7,26, 27,9,25		2						
Europa Orbiter	2018	3,4,7,21	2,7,11,17,24				3,4,21, 17,24					2,11						
Comet Sample Return	2018	1,3,4,7,13,17, 26,27	2,5,9,12,14				3,4,13, 14,17,14	5			26,27		1,7,2,9					
Venus in Situ Explorer	2018	1,2,9,12,14,28	3,4,7,8,21,22, 24,25				1,2,9,14, 28,3,4,7, 8,21,22, 24,25											
Aitken Basin Sample Return	2018	1,2,9,12,14,17, 25,27	3,4,7,18,21,24, 26				1,2,9,14, 17,25,27, 3,4,7,18, 21,24,26											
Planetary Defense Precursor	2019	1,2,3,4,5,7,13, 17,26,27	6,9,12,14,18, 21,23,24					3,4,5,13, 17,6,9, 12,14,18, 21,23,24				26,27	1,2,7					
MSR	2020	1,2,3,4,7,8,9, 12,13,16,17, 22,25,26,27,28	18,20,21,24						1,2,3,4,7, 8,9,12, 13,16,17, 22,25,26, 27,28,18, 20,21,24									
Mars Netlander	2021		1,2,3,4,5,7,8, 10,12,13,20, 21,27,28							1,2,3,4,5, 7,8,10, 12,13,20, 21,27,28								
Europa Lander	2023	1,2,3,4,7,9,12, 13,14,21,25,27	5,11,17,24,26									3,4,12, 13,14,21, 5,11,17, 24					1,2,7,9, 25,27,26	
Uranus Orbiter & Probe	2024	3,4,5,7	1,2,11,17,21, 24,28										3,4,5,17, 21,24,28				7,1,2,11	

Mission	Launch	Necessary Technologies	Enhancing Technologies	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Technology Identifier
Io Observer	2024	21	3,4,5,6,7,11, 16,17,23,24										21				3,4,5,6,7, 11,16,17, 23,24		
Lunar GEO Network	2024		1,2,3,4,5,7,9, 12,13,14,15, 18,21,24,25,27										1,2,3,4,5, 7,9,12, 13,14,15, 18,21,24, 25,27						
Saturn Probe	2024		1,2,3,4,5,6,8, 16,17,21,23, 24,28										1,2,3,4,5, 6,8,16, 17,21,23, 24,28						
Trojan Tour	2024	3,4,5,7,14,17, 20,24,26,27	1,2,6,11,12,13, 21,23,25										3,4,5,14, 17,20,24, 26,27,6, 11,12,13, 21,23,24				7,1,2		
Onboard GN&C Tech Tally, Essential			Integrated tally of essential GN&C tech's per year →	Indexed by matrix location (1,2,3,4/ 5,6,7,8, etc.)		,,1,1 1,1,, ,,, 1,,, 1,,, 1,,,1 ,,,	2,2,3,3 ,,, 2,,, 2,2,, 3,,, ,,, 1,,1,1	,,4,4 2,,, ,,, 3,,, 4,,, ,,, ,,,	,,, ,,,1 3,,,1 4,,,1 5,,, ,1,, 2,1,2,2		,,, ,,, ,,, ,,, ,,, ,,, ,2,3,	,3,5,5 ,,, ,,,2 5,3,, ,,, 2,,, ,3,4,	4,3,6,6 4,,, ,,, ,4,, 6,,,1 ,,,2 ,4,5,				5,4,, ,,2, 4,,, ,,, ,,, ,,, 3,,6,		1,2,3,4 5,6,7,8 9,10,11,12 13,14,15,16 17,18,19,20 21,22,23,24 25,26,27,28
Onboard GN&C Tech Tally, Enhancing			Integrated tally of enhancing GN&C tech's per year →	Indexed by matrix location (1,2,3,4/ 5,6,7,8, etc.)		,,, ,1,, ,,, ,1,, ,1,, 1,,1, ,,,	1,,2,2 ,,3,1 ,,, ,2,, 1,2,, 3,1,, 1,1,,	,,, 1,2,, 1,,, ,3,, ,3,, 4,,2,4 ,,,	,,, ,,, ,,, ,,, ,4,,1 5,,, ,,,	2,1,3,3 2,,4,2 ,1,,2 1,,, ,,,2 6,,, ,2,1,		,2,, 3,,, ,,, ,,1, 2,,1, ,,,2 ,,,	4,5,6,6 4,4,3,3 3,,1,4 2,4,1,1 4,5,, 10,,4,8 2,,3,2				5,6,7,7 5,5,4, ,,2, ,,,2 5,,, ,,5,9 ,3,,		1,2,3,4 5,6,7,8 9,10,11,12 13,14,15,16 17,18,19,20 21,22,23,24 25,26,27,28

Acronyms

AR&D	Autonomous rendezvous and docking
ARPOD	Autonomous rendezvous, proximity operations, and docking
AutoNav	Autonomous navigation
COTS	Commercial, off-the-shelf
CPU	Central processing unit
DARPA	Defense Advanced Research Projects Agency
DI	Deep Impact
DOF	Degrees of freedom
DS1	Deep Space 1
ECLSS	Environmental control and life-support system
EDL	Entry, descent, and landing
EP	Electric propulsion
ESA	European Space Agency
FDIR	Fault detection, identification, and recovery
FOV	Field of view
G&C	Guidance and control
GN&C	Guidance, navigation, and control
GPS	Global positioning system
HDA	Hazard-detection and avoidance
HEOMD	Human Exploration and Operations Mission Directorate
HRN	Hazard-relative navigation
IMU	Inertial measurement unit
InSAR	Interferometric synthetic aperture radar
IR	Infrared
JPL	Jet Propulsion Laboratory
LEO	Low Earth orbit
LIDAR	Light detection and ranging
MER	Mars Exploration Rover
MSL	Mars Science Laboratory
MSR	Mars sample return
NASA	National Aeronautics and Space Administration
NEO	Near-Earth object
OCT	Office of the Chief Technologist
PSD	Planetary Science Division
RADAR	Radio detection and ranging
S/C	Spacecraft
S/W	Software
SAR	Synthetic aperture radar
SMD	Science Mission Directorate
TAG	Touch and go
TanDEM-X	TerraSAR-X add-on for Digital Elevation Measurement
TPS	Thermal-protection system
TRL	Technology readiness level
TRN	Target-relative navigation
UAV	Un-crewed aerial vehicle

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