A Survey of Technologies Necessary for the Next Decade of Small Body and Planetary Exploration

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This work provides additional detail and justification for technology needs identified in the various white papers submitted by the Small Bodies Assessment Group (Mark Sykes, PSI), in particular:

- *Near Earth Objects: Michael Nolan, Cornell*
- *Asteroids: Dan Britt, University of Central Florida*
- *Comets: Karen Meech, University of Hawaii*
- *Dwarf Planets: Will Grundy, Lowell Observatory*
- *Centaurs and Small Irregular TNOs: Yan Fernandez, University of Central Florida*
- *Small Irregular Satellites: Bonnie Buratti, JPL*

Deep space reconnaissance and sample return missions will require a range of technology developments for maximum science return. These include propulsion technologies, telecommunication technologies, sensing technologies, guidance navigation and control technologies, sampling technologies, operations technology, advanced onboard processors, and autonomy technology.

Propulsion technologies: The natural progression of science missions from flybys to orbiters to landers to sample returns will require a corresponding increase in propulsion capability. The use of Solar Electric Propulsion (SEP) on Dawn reduced the cost of a multiple main belt asteroid rendezvous mission from a New Frontiers Flagship-class mission to a Discovery-class mission. Advanced SEP technologies promise to enable implementation of high priority science missions more cost effectively and at lower risk. These technologies could open up new and exciting science and exploration opportunities for the next decade, as rendezvous missions or multiple asteroid tours will frequently require low-thrust propulsion for success at reasonable mass and cost.

Current state of the art: Four low-thrust science missions have been flown, two by NASA (Deep Space 1 and Dawn), and one each by JAXA (Hayabusa) and ESA (SMART 1) [1]. Deep Space 1, which flew past asteroid (9969) Braille and comet 19P/Borrelly in 1999 and 2001 respectively, validated ion propulsion technology for deep space science missions. Dawn, launched in 2007, will orbit asteroid (4) Vesta beginning in 2011, then leave it in 2012 and orbit dwarf planet (1) Ceres in 2015. Both use SEP, in which solar arrays provide the power to ionize xenon and accelerate the resulting positive ions to a velocity nearly ten times that of the best chemical rockets, providing low thrust at a high specific impulse (in the range 1900s to 3100s). [2] In addition, there are currently over two dozen Earth-orbiting communication satellites currently using Hall effect thrusters.

Future needs: Traditional trajectories are mostly ballistic with a few propulsive maneuvers required to shape or correct the flight path. Low-thrust trajectories, by contrast, are characterized by long periods of continuous thrusting punctuated by occasional ballistic "coasts." As both the thrust magnitude and direction are controllable, and the duration and placement of coast periods can change, trajectory designers have far more freedom and a much larger trade space in which to work. The use of SEP for terminal approach to a target body can save propellant. Furthermore, future SEP missions will likely be characterized by one or more gravity assist flybys that add considerable complexity to find optimized low-thrust trajectories. Software tools developed specifically for low-thrust trajectory design are still immature, and additional investments in mission planning and trajectory design software are required to take full advantage of the capabilities that SEP provides.

The performance of solar arrays in terms of watts/kg has improved substantially over the past 4 decades. New solar array structures and cell technologies promise to continue and even accelerate this performance improvement. The Juno mission will use solar arrays at Jupiter. High performance solar arrays and advanced electric propulsion technologies could enable short trip times to Uranus and Neptune. Concentrator solar array configurations may enable all solar powered missions to destinations beyond Jupiter. At some point, however, solar power will be inadequate and nuclear electric propulsion (NEP) systems will be required instead. Hardware improvements for both SEP and NEP include:

- Electric Propulsion generic technologies (e.g. mission design, mission operations enhancements, very long-lived engines including Hall effect thrusters, low-cost power processing)
- SEP specific propulsion technologies (e.g. concentrator and/or high specific power arrays, dust barriers or elimination)
- NEP specific propulsion technologies (e.g. nuclear-thermal Stirling engines, small, light-weight reactors, radiation protection for instruments)
- Xenon cold gas propulsion for proximity operations and non-contamination

Telecommunications technologies: Depending on the range to a prospective target, science and engineering data return may be limited by bandwidth.

Current state of the art: Most deep-space missions use X-band links to transmit telemetry, while a few also use Ka-band to increase telemetry rates and science observation time (e.g., Kepler). The maximum rates are constrained by the aperture available at the DSN sites. Nowadays the 70 meter antennas provide the widest aperture in X-band, and 34 meter antennas at the three complexes have been built or retrofitted to operate at Ka-band. These 34 meter antennas can also be arrayed to provide additional aperture.

Future needs: The strategy that NASA chooses to increase very deep space mission communication bandwidth limits may require more or less technology development depending on the chosen solution. Extending the life of the Deep Space Network 70 m antennas may be the simplest but most costly development to support deep space missions. Concepts such as arrays of smaller antennas (e.g. 34m) operating at Ka-band are attractive from a cost and data return standpoint, while providing a radiometric navigation capability. Ka-band can also be used to perform more precise interferometric observations than are currently possible. Optical communication links offer tremendous downlink capability and, in principle, navigation capability, but this technology is still immature and needs substantial further development. For some applications, especially lunar exploration and on-orbit rendezvous, GN&C will require onboard interpretation of radiometric observables, which has not yet been done in deep space. The implementation of such a method will require the development of light-weight and accurate ultra stable oscillators (USOs), advancement of Doppler and Range signal interpreters, and navigation filtering systems for such data, especially from one-way data from beacons.

Sensing Technologies: Depending on the mission target, fast imagers of wide field-of-view for use in low-light environments will need to be developed. Light-weight medium-range LIDARs, RADARs or altimeters will be necessary for close proximity operations. Use of structured light systems can provide a means of using visual imagers for direct ranging. Gimbaling of sensors will greatly enhance science return by decoupling to a great extent the image planning process from the engineering needs of spacecraft body pointing, and appropriate low-cost and light-weight software and hardware systems should be developed.

Current state of the art: Deep space probes have been flying remote sensing instruments for nearly fifty years. Cameras, including infrared and ultra-violet sensors, magnetometers, and particle detectors have advanced very greatly in this time. Few LIDARs or altimeters are currently qualified for space operations. Voyager and Galileo showed the great advantages of gimbaling a suite of instruments, providing greatly enhanced sensing ability without resource conflict between telemetry. But gimbaling these instruments was expensive in terms of mass and cost, to the point that a gimbaled instrument suite similar to Voyager's was descoped from the Cassini development well before launch, the consequences of which have been dramatically increased operations complexity and cost and reduced science return.

Future needs: Capabilities of future missions, and the number of such missions that can be affordably flown will be determined largely by the ability to lighten, enhance, and make these sensors longer-lived, as well as capable of operating in the extreme environments of the outer solar system, Mercury and the more forbidding planetary atmospheres. Almost any instrument development which reduces the mass and increases the capability of a remote sensor will enable some form of important planetary investigation. Small light-weight instrument gimbals will greatly enhance science return by eliminating time resource conflicts between downlink and sensing, or even between experiments if each is individually gimbaled. The integration of existing instruments onto gimbals is itself a technology development, as the gimbal must provide precise pointing (both control and knowledge) while preserving the fidelity of the mounted instruments.

Autonomous Guidance, Navigation and Control: All missions making contact and many orbiting missions will require onboard autonomous GN&C. Deep Impact and Deep Space 1 used such a system, but for small body proximity operations this system would require extension. Landers and other proximity missions will need to detect and avoid surface hazards, even utilizing surface maps which are created onboard. Contact itself will challenge the spacecraft GN&C, inducing difficult-to-predict torques, and necessitating possibly complex safe ascent control strategies to insure departure without appendage contact. If a surface-sample-ejector technique is used (a mechanical dart that cores a sample and kicks the canister back toward the off-standing spacecraft) tracking, rendezvous and capture challenges will replace those of surface contact.

Current state of the art: Only two space missions have flown highly autonomous navigation systems which determined target relative positions and used propulsive maneuvers to guide the vehicle to specific target, and/or to update onboard knowledge of the location of the target for purposes of remote sensing: Deep Space 1 (DS1) in 1998 [4], and Deep Impact (DI) in 2005 [5]. These missions used the same system, "AutoNav," developed at JPL. (NEAR's landing on Eros was performed open-loop.) Both DS1 and DI had a relatively close flyby of a low-mass object, which – though requiring highly accurate measurement of subtly changing parallax on approach in order to estimate the impact parameter - did not (and could not) use knowledge of the physical nature of the target itself to perform navigation. Such linear fly-bys, though challenging enough, pale in comparison to the GN&C demands of certain classes of future missions, including those requiring precise and safe landing at a specific surveyed landing site, missions requiring a rendezvous with another vehicle, and missions requiring rapid adjustment of their orbits on a timescale incompatible with Earth-based control. All Mars soft-landers have used GN&C systems that closed a control loop on surface sensors, for altitude relative action, and in the case of the MER landers, surface relative velocity, but none navigated relative to known terrain, which will be required to explore specific areas of scientific interest as determined by orbital surveys.

Future needs: Autonomous GN&C systems will be required whenever position and attitude must be known precisely and updated quickly. A baselined multimission GN&C system, adapted as necessary to the peculiar needs of specific missions, will benefit:

- Flyby missions, when the time to encounter is not sufficiently well known in advance.
- Small body rendezvous and orbiting missions, using autonomous onboard landmark modeling and tracking.
- Missions in a dynamically tortuous gravitational environment may require course adjustment on a timescale of minutes, necessitating precise onboard terrain-relative navigation.
- Landing missions that intend to investigate specific sites will require LIDAR, RADAR or altimeter data as well as imagery, not only for terrain-relative navigation but also for hazard detection and avoidance.
- Atmospheric entry missions will require enhanced accelerometers, with wide dynamic range, to perform guidance through the atmosphere, with terminal landing operations as above.
- Missions that will perform deep space rendezvous operations, such as many Mars Sample Return concepts, will require autonomous rendezvous, involving specific trajectory planning capability and target-specific tracking systems.
- "Touch and Go" (TAG) sampling must cope with severe and unpredictable contact forces and torques.

All future autonomous onboard GN&C systems will require substantially more advanced navigation filters than those used by DS1 and DI, to handle a variety of data types and to solve simultaneously for position, velocity, attitude and angular rates.

Autonomous Planning Sequencing and Commanding: Having onboard command systems capable of dynamically reacting to conditions sensed onboard will enhance science return, reduce operational costs, and provide for greater mission reliability. As orbital conditions around small bodies are difficult to manage, it will be necessary to provide an onboard environment that can maintain the science objectives, just as the Autonomous GN&C system will react to the changing orbit.

Current state of the art: DS1 was perhaps the most autonomous spacecraft that NASA has yet flown, with the navigation system performing hours of unscripted activities to meet a range of navigation objectives. DARPA's Orbital Express mission also performed hours of autonomously generated events for the specific purpose of rendezvous and docking. For the MER rovers, long periods of autonomous roving, including obstacle avoidance, regularly takes place. In all of these events, custom C code was created for the specific task. For the SIRTF mission, a dynamically reactive and general command and control system, called "Virtual Machine Language" (VML), was created to respond to events onboard and take action accordingly [6]. This capability was expanded for Mars Observer and used extensively for responsiveness during aerobraking activities. This generalized autonomy language was further enhanced for Phoenix, where it was used to perform the entry descent and landing, and to provide the framework for much of the fault protection system. In another approach to autonomy, DS1 also flew a goal-oriented commanding system, as did the Space Technology 6 mission, with the Autonomous Science-craft Experiment that identified scientific targets of opportunity aboard Earth Observer-1 [3].

Future needs: As deep space missions become ever more complex, the need to reuse the ever-increasing size of the software systems will become paramount to achieve mission success and do so economically. Custom-designed autonomy software for specific applications will be ill-advised and unaffordable. Much of the costs of mission operations are consumed by the long-lead detailed planning of mission activities. By making these activities responsive to the current conditions onboard, and those conditions themselves guided by autonomous systems, this long term planning need not anticipate wide ranges of possible conditions, but the planning itself would entail specification of the activity intent, and the onboard systems then set to achieve those intentions. Goal-oriented, or otherwise dynamically responsive, sequence and commanding systems will be necessary to form the structures in which this autonomous GN&C, science acquisition, fault identification and recovery, surface roving, and generalized onboard activity programming takes place [7],[8].

Robust Mission Operations Ground Systems: Mission operations for deep space involve a carefully orchestrated sequence of planning and analysis tasks, including trajectory design, science and mission planning, sequence development, sequence and system testing and validation, uplink, execution, activity monitoring, system analysis and diagnosis, preparation of trajectory maneuver sequences, fault recovery and contingency planning. From beginning to end, the process can span months to years and add greatly to mission costs. Many opportunities exist to expedite mission operations, and though these enhancements often are linked to increasing onboard autonomy, they bring additional ground system challenges.

Current state of the art: Almost all missions are planned with long-lead-time sequence development, test and verification, frequently over a time-span of years. Usually, this is a result of the lack of ability of the spacecraft onboard systems to adapt to conditions determined onboard (such as current trajectory) or to respond readily and reliably to late changes in the planning. In the case of orbital surveys, development of surface mosaic imaging sequences is ideally done based on forecasts of current orbits, not on nominal trajectories. The Voyager mission 30 years ago demonstrated the utility of "movable blocks" of sequences that allow for the incorporation of late-developed trajectories (specifically time of flight knowledge), and the ability to easily apply time shifts to the sequences. Verification and testing of sequences before execution is often time consuming, and frequently takes longer than real-time in flight-system testbeds often to the point where such testing is not done, occasionally with dire results. Receiving, extracting, reformatting and analyzing data from missions in operations is critical to understanding and correcting mission behavior, but the process often forms a bottleneck for quick and cost-effective achievement of engineering team objectives.

Future needs: Aspects of mission operations that are today merely troublesome or inconvenient will be disabling in 10 years given the dramatically more sophisticated and difficult mission objectives of the future. Multi-month planning timelines will be untenable, and therefore tools to plan mission activities and resolve resource usage or objective conflicts rapidly will be necessary. Onboard autonomous systems will need methods of control and monitoring that are currently unprecedented. Testing of the complex commands that enable onboard autonomy will require new methodologies that rapidly probe a nearly infinite space of possible autonomous actions and converge on a best plan while testing for fault paths. New software testing strategies will be necessary to test these autonomy software systems in the development phase. New tools for mission analysis will be required to readily visualize onboard behavior and analyze and correct it if necessary. Science teams will need to respond to the mission environment as rapidly as engineers, quickly evaluating the fidelity of the onboard systems' adherence to their plans and objectives.

Sampling mechanisms: A wide spectrum of possible sampling mechanisms is possible: sticky-pads, brush-wheel samplers, corers, surface sample ejectors, and explosives. Each will likely require technology development. All will require some degree of mechanical and actuation support, including active deployment arms, release mechanisms, or capture baskets/containers. All will also require transfer mechanisms to move the samples to *in situ* analysis instruments or to Earth return capsules in an environment that will preserve the scientific value of the material.

Current state of the art: Sample acquisition and handling technology development is needed to enable *in situ* investigation and sample return from comets, asteroids, and small satellites. The Stardust mission brought back small particles collected from hypervelocity particle impacts into aerogel when flying through the coma of comet 81P/Wild 2. JAXA's Hayabusa mission attempted to acquire material ejected from the surface of asteroid (25143) Itokawa after firing a bullet into the surface. Hayabusa demonstrated a TAG mission scenario where the spacecraft briefly touched the asteroid for sampling. ESA's Rosetta, launched in 2004, is scheduled to land a deployable robot on comet 67P/Churyumov-Gerasimenko in 2014

Future needs: Future missions will need to acquire surface and subsurface samples from comets, asteroids, and small satellites such as Phobos and Deimos. Sampling can be done via various mission types including fly-through, touch-and-go (TAG), and lander missions. Fly-through missions reduce cost by eliminating the need for direct contact by the spacecraft with the surface, but currently they can sample only the coma of comets. Touch-and-go (TAG) missions enable direct surface sampling during the brief touch phase. Landed missions enable careful investigation of surface and subsurface samples but are more costly due to the added complexity of landing and adhering to the surface in the microgravity environment. Each mission type will benefit from technology development. Fly-through missions would benefit from generation of sampling material, e.g. via an impactor. Current TAG mission concepts require the spacecraft to come within a few meters of the surface to deploy the sampling device to the surface. TAG missions would benefit from development of sampling tool deployment mechanisms, such as via ejector darts or explosives, which enable the spacecraft to remain tens of meters or more from the surface. TAG missions would also benefit from technology enabling sampling of specified surface targets and acquiring samples below the surface. Landed missions would benefit from development of sampling systems enabling sampling at depths of 1 meter or more; the Rosetta SD2 sampling system represents the state of the art in sampling to depth in comets.

The various mission types would benefit from sample handling systems enabling distribution of samples to *in situ* instruments and return containers. Containerization technology is needed for sample return for hermetic sealing and cryogenic sample preservation. Sample measurement technology is needed to verify sample volume for return. It is widely held that a TAG sample return mission architecture provides desirable sampling capability with a low overall mission cost. JPL has been developing TAG mission technologies including navigation, surface sampling, sample measurement, and sample containerization. Further sample acquisition and technology investment is desired to improve the mission concept by enabling sampling with greater spacecraft stand-off distance, subsurface sampling, and distribution of subsamples to *in situ* instruments in addition to containerization for return to Earth.

More capable, flight qualified, rad-hard computers: The need for onboard computing capability continues to increase. Future small-body missions will rely on autonomous GN&C as discussed above. Regardless of the exact nature of proximity operations, the requirement to know accurately the position and attitude of the spacecraft and its components relative to the body's surface implies real-time processing and interpretation of various types of data (imaging, LIDAR, star tracker, IMU, etc.). To perform the GN&C function quickly and accurately will require an advance in the state of the art of radiation-hardened flight computers.

Current state of the art: The DS1 spacecraft used a RAD6K computer, and relatively simple operations of that mission during the flyby of comet Borelly consumed nearly 80% of the available processing, with GN&C occupying nearly half of that capability during peak operation, with image processing (the largest CPU consumer) operating every 60 s. The RAD750 computer was first used by Deep Impact in 2005 and is now flying on MRO and Kepler. With 10.4 million transistors and a clock speed of 200 MHz, it can process at speeds up to 400 MIPS. For the DI flyby of comet Tempel 1, a much more rapid sequence of images (every 15s) was possible, even though the image processing was substantially more complex. Even so, with a processor 20 times more powerful, only 60% of the CPU remained unutilized, allowing little room for growth of mission sophistication. Missions currently being designed for small body sample return, including "Touch and Go" operations will probably reach the capability limits of the RAD750.

Future needs: Within the next decade, missions will likely be designed to explore the highly dynamic environments of comet surfaces, the active geology of Io and/or the seas of Europa. Such explorations will require event planning, command and GN&C capabilities beyond those of the RAD750 in order for the spacecraft to remain safe and to achieve science objectives. Hardware-based image processing and data compression processors will offload some of the central processor requirement increases, but not eliminate them, and such co-processors will have to be radiation hardened and space rated. Along with the processors, memory demands will greatly increase commensurate with the increased data flux from the instruments, for example from much larger pixel arrays, and more precise spectral analyzers.

Operation in a dusty environment: Missions to comets will encounter a dusty environment which varies in both time and place. Dust may be a severe issue not only for imagers and solar arrays but for other sensitive hardware, and reliable dust prevention or elimination technologies need to be developed. Knowledge of the sources and time variation of dust production, and the resulting dust distribution, are of interest not only to the science community but also to the engineers flying the mission. The spacecraft G&C and navigation systems must have enough control authority to counteract dust impacts.

Summary:

- **Solar and nuclear electric propulsion** will require further technology development, especially nuclear. Tools for designing such missions, both trajectories and mission plans will be required.
- **Telecommunications** technologies will need to be enhanced, as many missions are and will continue to be bandwidth limited. Progress to shorter frequencies, including optical, must continue, while preserving the ability to use the com link for navigation.
- **Sensor technologies** will continue to enable missions by becoming more powerful and less massive and less costly. Increased power and versatility, especially through gimbals, will aid or enable both science return and navigation.
- **Autonomous GN&C** is an enabling technology for any future missions that must take difficult and dangerous action on a timescale shorter than the round-trip light time to Earth. Such autonomy also will potentially make missions more affordable.
- **Autonomous Planning Sequencing and Commanding systems**, along with autonomous GN&C systems, will be necessary to achieve demanding science objectives at reasonable cost, and to eliminate brittle years-long experiment design cycles.
- **Mission operations systems** must be advanced to make missions more capable and flexible and to manage the increasing levels of onboard autonomy that will be necessary, and to efficiently analyze the ever-increasing complexity of future spacecraft.
- **Sampling mechanisms** will have to be advanced to complete the sample return objectives from many solar system objects, where the diverse range of regoliths severely challenges current technology.
- **Advanced processors** will be necessary to perform many future missions whose challenging objectives are only now being envisioned.

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