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Small Body Exploration Technologies as Precursors for Interstellar Robotics

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Abstract

The scientific activities undertaken to explore our Solar System will be the same as required someday at other stars. The systematic exploration of primitive small bodies throughout our Solar System requires new technologies for autonomous robotic spacecraft. These diverse celestial bodies contain clues to the early stages of the Solar System's evolution as well as information about the origin and transport of water-rich and organic material, the essential building blocks for life. They will be among the first objects studied at distant star systems. The technologies developed to address small body and outer planet exploration will form much of the technical basis for designing interstellar robotic explorers. The Small Bodies Assessment Group, which reports to NASA, initiated a Technology Forum in 2011 that brought together scientists and technologists to discuss the needs and opportunities for small body robotic exploration in the Solar System. Presentations and discussions occurred in the areas of mission and spacecraft design, electric power, propulsion, avionics, communications, autonomous navigation, remote sensing and surface instruments, sampling, intelligent event recognition, and command and sequencing software. In this paper, the major technology themes from the Technology Forum are reviewed, and suggestions are made for developments that will have the largest impact on realizing autonomous robotic vehicles capable of exploring other star systems.

NOMENCLATURE

AI	=	artificial intelligence
APXS	=	alpha particle x-ray spectroscopy
AU	=	Astronomical Unit = 1.496×10^8 kilometers, the radius of the Earth's orbit around the Sun
CMOS	=	Complementary metal–oxide–semiconductor
CCD	=	charge coupled device
GNC	=	guidance, navigation, and control
EP	=	electric propulsion
g	=	acceleration of gravity at Earth's surface = 9.8 m/sec^2
I_{sp}	=	specific impulse = rocket's exhaust velocity/g
IR	=	infrared radiation
LIBS	=	laser induced breakdown spectroscopy
LIDAR	=	light detection and ranging
NEP	=	nuclear electric propulsion
REP	=	radioisotope electric propulsion
SEP	=	solar electric propulsion
TAG	=	touch-and-go
UV	=	ultraviolet radiation
VML	=	virtual machine language
Δv	=	velocity change

1. Introduction

The scientific activities undertaken to explore our Solar System will be the same as required someday at other stars. It is probably the case with all stars having planets that relic small bodies contain clues to the early stages of a solar system's evolution as well as information about the origin and transport of water-rich and organic material, the essential building blocks for life. For these reasons, they will be among the first planetary bodies explored when a new star system is entered by future robotic spacecraft. The small body and outer planet exploration technologies developed in our Solar System will form the technical basis for robotic explorers at other stars. Independent of how a space vehicle will traverse the interstellar distances, the smaller, specialized robotic vehicles it will carry with it to another star system will have a heritage of autonomy, power, propulsion, and scientific instrumentation directly related to the exploration of our star. The focus of this paper is on these robotic explorers which will operate within the star system.

The systematic exploration of primitive bodies throughout our Solar System has just begun and will require new technologies for autonomous robotic spacecraft. Any robotic vehicle travelling outside the sphere of useful solar power (a few AU from our Sun) and more than a light-hour in communication range must essentially be independent and self-sufficient in terms of onboard propulsion, power, and autonomy. Current missions include the Dawn robotic mission to rendezvous with asteroids Vesta and Ceres, the Rosetta comet rendezvous mission, and the New Horizons flyby mission to Pluto-Charon and beyond. In the coming decades, it is hoped that a progression of small body missions will push the exploration horizon outward from the asteroid belt, to the cometary and asteroidal objects (Centaurs and Trojans) in proximity to the giant planets (5-30 AU), the trans-Neptunian objects and dwarf planets (30-100 AU), the Kuiper Belt Objects (100-1000 AU), and finally the Oort Cloud (> 1000 AU). These missions will demonstrate most of the robotic technologies needed to explore a star system. Two key attributes for interstellar robotic explorers have already been partially mastered: longevity and storability. Voyagers 1and 2 were launched in 1977, exited the Solar System to interstellar space, and are expected to operate at reduced capability until about 2020, or more than forty years, limited only by attitude-thruster propellant and radioisotope electric power. All indications are that if resupplied with consumables, these vehicles could operate for several more decades.

The direction of exploration at an extra-terrestrial star system is reversed compared to our Solar System. The primary interstellar robotic vehicle(s) carrying its family of smaller explorer craft will arrive from outside of the star system. This parent craft will encounter several primitive bodies in the outer regions first and deploy robots to explore these. The initial studies provide benchmark measurements of compositions to compare later with objects of the inner solar system. The parent craft will perform long-range radio and optical observations of the entire star system, select the most promising objects, and then direct the exploration sequentially in steps inward toward the star. It is energetically expensive to move outward again so the exploration strategy will be a set of chess moves down the gravitational well, visiting the planets and small bodies along the way, and in some cases leaving orbiters to do long-term studies. The parent craft may park at some location in the outer solar system to continue long-range observation and send robotic emissaries into the inner solar system.

Small bodies are more varied and far more numerous than planets and are spread throughout a star system. Depending on their location, they can be either some of the easiest to reach and explore (like near Earth objects) or the most difficult. In our Solar System, the goal is to characterize and understand the different populations of small bodies in-situ. This is made difficult by the limited number of missions possible. Remote identification and assessment using optical, thermal, and radio imaging are essential. The same problem of limited resources will be faced by robotic explorers travelling to other star systems. Only a fraction of small bodies are easily accessible. Within a star system, remote survey observations will occur first, and detailed studies of special objects will be performed later once intelligent choices can be made by the robotic parent craft. The range of mission options increase in complexity from fly-bys (remote sensing and micro-sample capture), rendezvous (proximity studies), lander or touch-and-go (TAG), and finally sample recovery and study or utilization at a local robotic lab (sample return to Earth from a star is not considered timely or feasible). These latter missions are so resource-intensive as to be reserved for only the most scientifically interesting objects in the star system. Planetary protection becomes paramount since any potentially life-bearing or hospitable world could be irreversibly contaminated by a lander if the craft has any trace biochemical remnants (unlikely but possible after decades in space). Remote sensing instruments for detecting potential biochemical signs at the surface or in the atmosphere are necessary technologies still to be perfected. Capabilities not present in today's robotic vehicles that will be essential at another star are repair, refueling, and reuse. After travelling for many decades to reach another star with robotic vehicles in hibernation, the stock of probes will be depleted in a short time if they are used once and left to decay around the exoplanetary system. Resupply and reprogramming of used vehicles is a development in our Solar System that must be mastered in order to make long-term exploration of other stars possible.

The characteristic that will most distinguish interstellar robotic explorers from those within our Solar System today is intelligence. Being light-years away from any human contact, there simply is no alternative than for these machines to be imbued with some central or distributed artificial intelligence (AI) to make decisions and adapt to the unexpected. The parent craft will have to intelligently collect, filter, analyze, interpret, and transmit data to Earth. The data that is received decades later at Earth from our robotic emissary cannot be interrogated or replied to on any time scale that can reasonably affect the transmission. It is what it is, and without intelligent filtering and a context from the sender, it will become a confusing "stream of consciousness" to people on Earth. Most of the smaller robotic vehicles will require only a rudimentary intelligence, but still at a level of autonomy our robots do not have today. Reduced intelligence is required for these smaller probes since they must only be operationally independent for periods of days, and they can communicate with the parent craft for updated instructions. Their intelligence will be the same as developed and fully qualified for future robotic explorers in our outer Solar System. The form of robotic governance best suited to guide the exploration is unknown today, and we have no experience with this. The robotic explorers could have a command hierarchy (analogous to Mission Control directing a fleet of vehicles) or they could act as a hive of independent, self-organizing beings which act communally. It is also possible that a hybrid of these two governance forms may be optimal with teams of robots acting semi-independently, but regularly conferring among groups to make high-level decisions about the science campaign. Fortunately robotic governance can be tested and adjusted within our Solar System long before it is needed at another star.

The understanding of technology needs for autonomous small body exploration in our Solar System has just started. The Small Bodies Assessment Group (SBAG), which reports to NASA initiated a Technology Forum in 2011 that brought together scientists and technologists to discuss the needs and opportunities for small body robotic exploration [1]. Presentations and discussions occurred in the areas of mission and spacecraft design, electric power, propulsion, avionics, communications, autonomous navigation, remote sensing and surface instruments, sampling, intelligent event recognition, and command and sequencing software. The slide presentations of the Forum speakers, the meeting transcripts, and notes of the panel discussions are archived on the SBAG website in Ref. 1, which represents a unique overview of emerging robotic technologies. Many technology needs for small body science are the same as for outer planet exploration [2]. Most of the highest priority investments for outer planet technologies such as power, propulsion, surface mobility, landers, and in-situ science instruments will also benefit small body science. In this paper, the major technology themes from the SBAG Technology Forum are reviewed, and suggestions are made for developments that will have the largest impact on realizing autonomous robotic vehicles capable of exploring other star systems.

A robotic exploration vehicle is analogous to an independent human explorer. The vehicle is made up of spacecraft systems, exploration systems, and scientific instruments. Spacecraft systems are like the basic human organs, neural trunks, skeleton, and muscles, which allow a human to survive and function. These provide on-board services and maintain functions of the robotic vehicle, and include electric power, propulsion, communications, and avionics. Exploration systems are like the higher brain functions, tactile abilities, hands, and limbs which allow a person to analyze and solve problems, learn, coordinate, and act on the environment. These systems affect the science tasks and provide the supporting matrix for the scientific instruments. They include in-space guidance, navigation and control (GNC), surface GNC, surface landing and mobility, sampling hardware, event recognition, and command and sequencing software. Finally scientific instrumentation is similar to the senses which allow a human to experience and measure the environment and collect information. These are highly specialized for the particular measurements planned to explore the celestial body, and often they are seamlessly connected to the exploration systems due to uniqueness of the mission (e.g. sampling and analysis hardware). The two broad instrument categories are remote-sensing and in-situ instruments (roughly anything intended for within a meter or less of an object). Generally developments and improvements in one vehicle system can lead to new capabilities realized or enabled in another. A well cited example is how deep-space electric propulsion can expand the science program by delivering instruments to previously inaccessible objects while the concomitant extra electric power increases instrument power and data transmission rate [3, 4].

Mission design and spacecraft design are closely coupled from the experience we have gained within our Solar System [5]. For robotic vehicles, no one size fits all missions, and there is no standard robotic vehicle. Cost prohibits developing generic vehicles today because resources are only available for the scope of one mission. We still do not know how to design generic vehicle hubs with "plug-and-play" peripherals for exploration systems and instrumentation that can be easily interchanged. At a remote star, this will be an enabling capability for building up robotic explorers for specific missions after arrival at the star. It is unlikely we will be able to predict the preferred combinations of instruments ahead of time for the different bodies encountered. The main classes of robotic vehicles for small body missions are flybys, rendezvous orbiters, landers or touch-and-go (TAG), and sample return. No formal standards for design margins exist, but it is appreciated that the mission design must be robust against missed thruster periods for successful rendezvous with objects.

Inclination plane changes are avoided as too expensive in propellant, so most exploration is done in the plane of the Solar System. The largest technology gaps are for sample return since those designs are most sensitive to the actual on-the-ground environment. For small and medium sized robotic vehicles (< few thousand kg), in-space propulsion development is focused on gridded ion thrusters (accelerated by electrostatic grid), Hall Effect thrusters (ions accelerated by magnetically confined electron plasma), and chemical thrusters. More than one of these may be on the spacecraft depending on thrust needs for transfers, course correction, rendezvous, landing, and ascent. Ion (for $I_{sp} > 3000$ sec) and Hall ($I_{sp} < 3000$ sec) are both low-thrust electric propulsion (EP) and ideal for the weak gravity of small bodies, for mega-multiple flybys, orbiting, and even touching down on small bodies. Electric power will likely come from solar, radioisotope, or a nuclear reactor source, but solar is only useful where sunlight is reliably available. Nuclear thermal propulsion ($I_{sp} < 1000$ sec) in which a working fluid (e.g. water or hydrogen) is heated and directly expelled for thrust is more appropriate for larger vehicles operating in deep gravity wells where high thrust is needed (near planets but not for most small bodies).

Independent of the thruster used, propellant is the largest consumable by mass, and this implies the need to locate the liquid and ice consumables for refueling soon after arrival at a star. Indeed the lifetime limitation of current robotic vehicles is not due to hardware but consumables. Automated mining and refining capabilities will be needed for any long-term robotic presence at a star. Reducing the amount of mined resources as much as possible is desired. An important development at least for low mass robotic vehicles will be propulsion without propellant such as solar sails (light pressure) or magnetic sails interacting with the solar plasma wind. Sails are probably most useful in the inner solar system, and a bi-modal sail which has electric generation woven into the sail would be an added benefit. Sail-craft need to be lightweight to take maximum advantage of the sail thrust, so there will be the attendant need for miniaturization of all spacecraft components to lighten the vehicle.

This initial look at robotic exploration in our Solar System leaves us with some broad technological developments needed for future star exploration. Within the constraints of sub-light speed interstellar travel, the robotic spacecraft must be storable and capable of hibernation for many decades before arrival at the star system. Remote survey observations of the star system for interesting primitive bodies, sources of consumables, and any planets are the first tasks, the motives being both practical and scientific. Resources will be limited and in-situ supplies only inferred for the vicinity of the star. Mining for consumables will be necessary for a long-term presence. Remote sensing flyby missions and rendezvous missions of multiple bodies to broadly map out the solar system implies the need for long-life, efficient electric propulsion, and both solar and nuclear/isotope electric power. Propulsion not requiring consumables such as sails is needed to reduce dependence on local resources. Plug-and-play robots built up with interchangeable parts around a few generic hub choices (fly-by, orbiter, lander) are very desirable to tailor the spacecraft to a mission without wasting propellant to transport unnecessary components. Some vehicles will be expendable in harsher environments, but most spacecraft will have to be capable of repair, refueling, and reprogramming. Finally, there is the need for different levels of intelligence and autonomy depending on the time period between instruction updates, complexity of tasks, and responsibilities for event recognition and data filtering. With these general considerations in mind, we next review specific technologies for autonomous robotic exploration in our Solar System and suggest innovations necessary for interstellar robotics.

2. Spacecraft Systems

Spacecraft systems provide basic services and maintain the functions of the robotic vehicle. These include electric power, propulsion, communications, and avionics. Spacecraft systems deliver and support the Exploration Systems and Scientific Instrumentation at the science target, which are discussed in the following sections. Innovation in spacecraft technologies is one of the most powerful ways to leverage new science capabilities since the targets are often difficult to reach and operate near. For example efficient ion propulsion has made possible the multiple asteroid rendezvous in the Dawn mission, and rover technology has expanded Martian science by opening up huge surface areas for exploration. In this section the emerging technologies for robotic spacecraft systems operating within our Solar System are discussed and extensions needed for autonomous exploration of other stars are suggested. The technologies for interstellar flight are not within the scope of this paper, and these are discussed by other authors at this Symposium.

Electric power for robotic spacecraft will likely come from a combination of solar, radioisotope, and nuclear reactor sources since all three are well understood for self-contained, independent vehicles [6]. The first two have been reliably demonstrated on many missions with successful multi-decade operations, but the third needs development for large robotic explorers requiring more than 10 kW of power. The electric power system is comprised of a generator, power management, distribution, and storage. Its mass has traditionally been about third of the robotic vehicle, with propulsion, avionics, and structure about a third, and payload also about a third or less of the total mass. In our Solar System, electric power sources for robotic vehicles are solar, nuclear/isotope, batteries, and fuel cells. We do not have fuel cells and batteries with multi-decade lifetimes, but rechargeable 30-50 kilocycle batteries are in reach. Storage devices also must be capable of long-term hibernation for trips to distant stars. Chemical fuel cells will require refueling and in-situ resources. Solar cells today produce 100 W/kg of system mass with an efficiency of 25 percent at 1 AU from the Sun. The desired goal to meet future solar electric propulsion and instrument needs is >250 W/kg at 35 percent efficiency. Solar power is only available within a few AU of the Sun.

Nuclear power is used when sunlight is absent or unreliable and includes both reactors and radioisotopes. A nuclear reactor requires a minimal critical mass to maintain the reaction and so is appropriate for large vehicles (>10,000 kg) requiring >10 kW. But it does have a bi-modal option in which it can be used for both electric power and thermal propulsion. Radioisotopes produce heat by radioactive decay and require no complicated machinery. They are demonstrated, long-term heat sources for generating electricity and can be stably packaged in kilogram amounts for space use. In gram quantities they are also used to heat sensitive components in a spacecraft. Radioisotope generators today based on thermoelectric cells produce 5 W/kg of system mass at six percent efficiency, which is adequate for some instruments but not electric propulsion. For future deep-space applications, the goal is >10 W/kg at 30 percent efficiency using thermo-photovoltaic, thermoelectric, or dynamic generators. Plutonium-238 (86 year half-life) has been the standard isotope used to date because it mainly decays by alpha emission with few neutrons and was available from nuclear weapon construction. It can provide about 500 W of heat per kilogram of isotope. Due to the Pu238 dwindling supply, Am241 is now being considered by the European Space Agency as an alternative for deep-space power. The 430-year half-life of Am241 makes it well suited for long interstellar voyages. Long-life radioisotopes either have to be taken on the interstellar voyage, extracted and processed in-situ, or produced from a nuclear breeder reactor on the parent craft.

In-space propulsion options for robotic vehicles today are chemical, electric, and nuclear thermal [7]. Sail propulsion can eliminate the propellant but has yet to be used on any space science mission. It is potentially useful for inner Solar System flyby and orbiter missions where no contact with a body is called for. Sails become effective thrusters at 1 AU when the areal density is a few grams per square meter, which is achievable in the near term. But the sail area may be of order a square kilometer for a robotic sail-craft, so deployment and control must be mastered. Chemical propulsion is used for deep-gravity wells, transfer, injection, landing, and ascent. It is a reliable option for low Δv maneuvers (~ few km/sec). The low exhaust velocity of chemicals (< 3 km/sec) means large propellant fractions are usually needed. Chemical fuel and oxidizers for refueling will have to be refined from feedstock on small bodies, moons, and planets. Electric propulsion is for high-energy, low-thrust transfers in deep space, orbit correction, servicing, cargo transport, and formation flying. High exhaust velocities above 15 km/sec reduce propellant mass, making it ideal for high Δv maneuvers. It needs electric power and inert propellants, which at a distant star system must be located and refined by robots. It is a high-tech option requiring power generator, power processing unit (PPU), thruster, steering gimbals, and feed system. The source of electric energy gives rise to the nomenclature solar electric propulsion (SEP), suitable near the Sun, radioisotope electric propulsion (REP), and nuclear electric propulsion (NEP) when a reactor used. Ion erosion of thruster components limits the lifetime and propellant mass throughput. Variable specific impulse is available and desired for the different gravitational fields encountered during a small body mission, including possible contact on a surface without the need for a separate lander. Nuclear thermal propulsion is for high-thrust in gravity wells of planets as well as deep-space transfers of large vehicles. The specific impulse is usually < 1000 sec due to nozzle thermal limits, and water can be used as the in-situ propellant. The nuclear engineering is understood, with known lifetimes, but a large on-board nuclear inventory is needed. As noted, bimodal operation is possible to provide electricity as well as thrust from the nuclear reactor heat source.

Avionics encompasses all the ancillary support electronics and equipment that controls and maintains the spacecraft [8]. These are necessarily radiation tolerant and in fact are best designed by being more transparent since thin shielding causes damaging nuclear showers. Avionics are also cold-tolerant and a move towards no-thermal management and cold blooded vehicles is underway. In a degraded mode of operation, the avionics must be reconfigurable. Avionics for the next generation of robotic explorers in our Solar System will support autonomous operations, instruments, and data processing with only occasional outside instructions. The hardware is moving towards complete avionics-on-a-chip, multi-function wafer structures, stacked silicon through-via technology, and modular, standard blocks (so-called plug, play, replace). This is an area where the advances are underway today that will be directly applicable to interstellar autonomous, plug-and-play robotic vehicles.

Communications for interstellar robotic vehicles come in two main categories: the link between different spacecraft within the solar system and the data link to Earth. Communication with Earth across many light-years distance is not covered in this paper since this is a topic discussed by others in this Symposium. The basic communication metric is data transmission rate, and this is proportional to the product of power, antenna area, and radio frequency squared divided by distance squared. Long distance communication benefits most from high radio frequencies. Communications with adequate transmission rates out to 30 AU use available power sources at high radio frequencies in the Ka-X-S bands, (1-10 cm wavelengths) [9,10]. The tera-hertz frequency range (30 micron to 1 mm) is still in need of a solution because in this gap there are limited methods to generate continuous radiation at the needed power levels. Development of lightweight, 10-100 W, tera-hertz sources and antennae would be a significant improvement for high-data rate communications. Without a tera-hertz solution, the emphasis is to develop optical systems (0.1 - 10 micron lasers) for the post 2030 time frame. By the time interstellar voyages begin, communication technologies for data transmission over hundreds of AU within our Solar System will have been perfected.

3. Exploration Systems

Exploration systems are the specialized technologies that carry out the science program and provide a supporting matrix for the scientific instruments. These systems include in-space guidance, navigation and control (GNC), autonomous surface GNC, lander technology, surface mobility, sampling hardware, event recognition, and command and sequencing software. Within autonomous GNC is computing and artificial intelligence. Because all these systems must operate in unique and often harsh environments, solutions for exploration technologies are often specialized for one type of object. This design problem is more complicated at or near the surface since those conditions are the most variable and unpredictable. Although reuse and recycling are important with limited resources, robotic exploration in other star systems may still require some expendable vehicles in environments where retrieval is difficult (e.g. a comet surface).

Autonomous GNC for in-space navigation is not fully realized yet but the first flight applications are in progress [11]. The Rosetta spacecraft of the European Space Agency will attempt this on a limited scale during its comet rendezvous in 2014. This technology is essential for future star system explorers. A key development still to be perfected is fully integrated six-degree of freedom GNC which is not standard today. During approach and in proximity to objects, attitude and translation must be optimized in real time to accomplish science measurements and sampling. In close range maneuvering within a few meters distance this involves imager and antenna pointing, surface avoidance, and solar panel attitude and reaction to vehicle motions. During contact for sampling or in-situ measurements, reaction forces must be compensated to maintain orientation and to respond to active environmental disturbances such as gas venting or dust. To reduce the landing position errors below 10 meters, landmark-based navigation and image-based feedback control are needed during the approach from about 10 km down to one-meter distance. The navigation computer must perform shape modeling and on-board mapping including terrain heights from radar or laser ranging. The autonomous GNC achievable today can process one image every 15 seconds with 10 landmarks per image, and this is just adequate to yield a 5-10 meter spot error and 3-5 cm/sec velocity error. Higher imaging rates and more landmarks are desired to reduce risks from false matches, poor lighting, sparse features, view angle changes, and scale changes. This may necessitate a dedicated GNC processor, faster CPU, and dedicated hardware for image processing.

The reason for seeking access to a small body surface determines the local mobility required. If the purpose is to interrogate a surface to determine chemical composition and physical properties at numerous locations, then touch-and-go (TAG), hopping, or rolling may be options. Autonomous surface navigation is complicated on small bodies by weak gravity [12]. Navigation is primarily a mobility issue. For a standard small body density of 2 grams/cc, a 300 meter diameter object has a surface gravity of about 10 micro-g and an escape velocity of about 30 cm/sec (both linearly proportional to diameter). There is a poorly defined vertical in low-g so a wheeled vehicle can become misaligned and flip over. Self-righting mechanisms are needed. For rovers, slow rolling is required to maintain surface contact and keep the ballistic trajectory within a wheel radius of the contact point. This is given by the condition for speed $v < (Ra)^{1/2}$ where R is the wheel radius and a is the local acceleration due to gravity. This usually means speeds in the range of mm/sec to several cm/sec, which makes it very time-consuming to explore large areas. For gravity less than some minimal value, wheeled modes of transport are probably not worth considering for the complexity introduced. Object avoidance by imaging feedback is feasible at low speeds, but rapid changes in lighting and perspective make this difficult on irregular, rocky surfaces or where gas and dust venting occur. Hopping rather than roving may be preferred to cover larger areas if there is a means to prevent bouncing with a landing impact absorber. An alternative to hopping is the use of EP thrusters to make multiple soft landings and liftoffs with little propellant use. In either case there needs to be a smooth hand-off between surface and in-space GNC operations to control the vehicle as it moves from surface to space and then back to a landing.

In the transient environments of small bodies such as comets, large data rates may be required for environmental characterization in support of operations, so intelligent data filtering and event recognition onboard the spacecraft are needed [13]. New phenomena in many cases are signaled by environmental changes detected by imagers. Event recognition usually involves imaging, its quantifiable characterization, responding to changes by taking more data and gathering statistics, or ignoring the event using some criteria and carrying on with the observations. The technology is well established on the Earth Observing One (EO-1) satellite that measures terrestrial surface and atmospheric phenomena and on the Mars rovers. Thousands of images have been processed and transient phenomena successfully recorded. Autonomous thermal imaging on EO-1 regularly detects new volcanoes and wildfires, changes in ice sea flows, snow on sea ice, and sulfur on ice, and the imagers on Mars rovers automatically detect and record transient dust motion on the planet surface. A key development needed is to integrate a wide range of possible event responses with on-board GNC to coordinate the science instruments with the motion of the vehicle.

As the robotic vehicle navigates and takes data in space or on a surface, it uses command and sequencing software to operate independently for periods of many hours through critical phases when real-time decisions are needed. Sequencing applies a constrained set of actions (commands) to operate the spacecraft. Sequencing has moved away from time-ordered commands to logic-guided sequences with timing determined by conditions present and reusable elements or scripts that can be rearranged by occasional updates of mission instructions [14]. Sequence elements allow common functionality to be modularized and reused within the GNC. The next advance on the horizon is distributed, coordinated decision-making which is reactive, makes real-time choices with available information, has fault detection and response, and has a re-planning capability. Once implemented in our Solar System, this will form the basis of smart command and sequencing for interstellar exploration, but probably with some added level of artificial intelligence (AI) for initiating unplanned activities based on field discoveries. Since 1998 sequencing has been implemented by virtual machine language (VML) on 12 NASA missions with 44 flight years of experience. VML enables parallel and serial execution of activities, absolute time-tagged master sequences (engineering and science), reusable software blocks for automated engineering and science activities, libraries for holding engineering and science instruction blocks onboard, objects for instrument operations, and parallel state machines for coordination of complex activities such as landing, sampling, rendezvous, and docking. Micro-sequencing can be applied to scientific instruments by treating them as “tiny spacecraft” with a serial input-output connection. Today VML-based sequencing is under development for entry, descent, landing (EDL), autonomous navigation for asteroid touch-and-go, and sample return from the Martian surface to an automated rendezvous in orbit.

Robotic exploration of celestial bodies involves both remote sensing and surface contact to measure or sample the object. Sampling hardware is often closely coupled to the in-situ scientific instruments (next section). The basic samples to be collected, analyzed and retrieved at small bodies are gas, dust, and surface material. The latter includes material brought up by sub-surface coring or trenching where complex organic materials may be protected from radiation. In the present era the emphasis is on fly-through, touch-and-go (TAG), and landing missions to retrieve samples for return to Earth [15]. But these challenge today’s capabilities. The fly-through mode involves either passing into a comet halo (e.g. Stardust at Wild2) or using an impactor to drive material into space which is collected. Hayabusa-1 attempted the latter with a projectile fired at the surface of near-Earth asteroid Itokawa, and returned thousands of dust grains to Earth in a re-entry capsule [16]. The TAG mode will require developing robust sampling deployment tools for the brief contact when the vehicle approaches the surface and then ascends. The landing mode is for careful surface and interior sampling during an extended stay. Tools for deep coring and extraction need development. Lander missions can involve both in-situ analysis and sample return. There is a lack of sophisticated down-hole in-situ analysis technology. As a result core samples must be transported to the surface for even a cursory analysis. In the next two decades there will be a need for smart sampling systems to choose material, in-situ micro-analytical technologies, and sample verification technologies for small body exploration. Sampling is severely constrained by limited spacecraft resources (power, volume, mass, computational capabilities, and telemetry bandwidth). In our Solar System it will demand innovative miniaturization and advanced component design for integrated sampling systems that can survive and operate in challenging environments (extremes in temperature, pressure, gravity, vibration and thermal cycling). There is very limited experience in planetary and small body sample acquisition, in particular, for astro-biological and subsurface liquid and icy samples. These are probably the most important samples to be acquired from primitive bodies in another star system. Cryogenic sample acquisition and handling are undeveloped technologies but are needed for comet ice retrieval.

The development of exploration systems is very dependent on the relative emphasis on remote or in-situ science at an object. In both our Solar System and at a distant star, autonomous GNC for accurate landing, TAG, and surface hopping for multi-site visits on the same body is needed to bring landing errors to a few meters. Interestingly, the need for rovers as separate from hoppers is not yet decided in ultra-weak gravity. Rover mobility adds mass, complexity and the unpredictable, uneven surface of comets and asteroids may limit rover speed and effectiveness. On a large, smooth body, rolling is more energy efficient for short treks, but small bodies may be best studied at two or three well-separated sites. For surface studies, there is a need for deeper (>30 cm) sampling for regolith, rocks, ice, and organic materials. To guide interstellar robotics design, we need an understanding of the breadth of space organics anticipated, their detection, and identification in-situ, and the best approach to astro-biological investigation. Today it takes sophisticated Earth lab analysis to unambiguously detect amino acids in comet samples. At a distant star, our robots need this capability at a landing site or the robotic parent craft must possess a chemistry lab onboard to process returned samples for biochemical signs. This suggests an intriguing possibility in our Solar System that could change how we do small body science. For the exploration and sample return from small bodies at 30-100 AU a robotic space station can be parked in the outer Solar System to serve as a collection point and automated chemistry lab. This station could be occasionally resupplied and even upgraded over decades of use, thus increasing the amount of samples studied in the outer Solar System by orders of magnitude. Only the most exceptional samples culled from the many studied will require a return to Earth.

4. Scientific Instruments

The scientific instruments are perhaps the most specialized items on the robotic vehicle. The instruments are for the particular measurements planned to explore the celestial body. The two broad categories are remote-sensing instruments [17] and in-situ instruments [18]. In-situ instruments are intended for within a meter or less of an object, and include real-time, sample analysis instruments. Interchangeable plug-and-play instruments mounted on a generic spacecraft bus will be a necessary development for interstellar probes, permitting robots to build up customized vehicles on the spot and omit unnecessary instruments for a particular object. We do not know how to make robotic vehicles with interchangeable parts today, but for small bodies it may make sense to develop standard vehicles for different object types. For example a fly-by or rendezvous with most cold, small objects will usually require IR/optical imagers, UV-IR spectrometers and imaging spectrographs for mineralogy, magnetometers, mapping/penetrating radars, and laser altimeters. Warmer objects with halos like comets will require the vehicle to always carry the same UV and optical spectrometry to decipher the complex, transient emissions from the surrounding gas and dust cloud. But in the present era, limited funding does not permit the development of generic vehicles, and mission design and vehicle design are closely coupled, resulting in unique spacecraft.

Basically all data collected by the spacecraft starts as an analog signal. Increasingly the move is to convert this analog signal to a digital signal as close to the instrument front-end as possible. This early digitization reduces the need for faithful analog transport over the spacecraft cable system and enables programming flexibility and on-chip processing. Remote sensing instruments are benefiting from mass and power reductions due to increased use of integrated single chip devices which include data filtering and processing. This is particularly true for imagers, which are one of the most common devices on spacecraft and used to collect radiation over the IR to UV spectrum. Space imagers are increasingly based on complementary metal–oxide–semiconductor wafers (CMOS) instead of charge coupled devices (CCD) since there is no need to move charge across the face. Instead charge is read from each pixel into the back plane. CMOS is also easier to make radiation hard with integrated processing electronics on the same chip, which may be essential for surviving long interstellar voyages. To widen the spectral range, imagers are also being made of diode arrays with expansion to UV fluorescence imaging. A new direction is integrated imaging and spectroscopy within a single device. Thermal imagers are based on HgCdTe cooled focal plane arrays for near, mid, and far IR by varying the relative elemental composition. But cooling requires long-life cryo-coolers, which is a limit today, or passive cooling systems depending upon shielding and radiation into space. A cryocooler can be thermodynamically reversed in principle to form an electric generator powered by a heat source. Dynamic radioisotope electric generators and cryo-coolers have similar life issues. Uncooled bolometric arrays are reaching large sizes of 1024 pixels square. Optical lenses are becoming aspheric to reduce number and graded-index to eliminate aberrations, and auto focus and zoom will become standard in the near future. Magnetic measurements can take up less payload mass with digital fluxgate magnetometers which reduce the mass from 4 kg (analog magnetometer) to 0.4 kg. Fiber optic and disk lasers are evolving now for lightweight, power-efficient LIDAR (Light Detection And Ranging) applications.

There are many innovations that would dramatically improve science from remote sensing during a fly-by or orbital operations at a small body. A serious shortcoming is the capability to measure atomic compositions during a flyby with active gamma-ray instruments (compact neutron generator) and active x-ray instruments. These will require new large area solid state x-ray detectors and neutron detectors with good energy resolution for water and ice detection. Gamma, x-ray, and neutron spectrometers are primary for composition measurements and need significant development. Long-life cryo-coolers need development for high purity Ge gamma detectors and HgCdTe thermal imagers. Reflective optics are moving toward carbon fiber replicas for meter-class, sub-kilogram mirrors, and silicon carbide and carbon fiber composites need to become standard for ultra-light optical benches, structures, and fixtures. Electrically steered, active pixel, sparse phased-array radar antennas require development to investigate the detailed internal structure of objects.

In-situ instruments are intended for use at the surface or within a meter of the object. The weak gravity of many objects means that multiple close approaches and landings are achievable with EP thrusters. For asteroid exploration there may be no need for a separate lander. But for comets the surface environment may be transient and damaging so the orbiter would need to maintain a safe distance. The architecture of a lander attached as a subunit of a larger orbiter has been used on a number of planetary missions. Instruments for the Rosetta Philae lander and the Martian Surface Lab (MSL) are laying the foundation for self-contained, in-situ analysis stations. The problem is that with today's technology, high-precision compositional measurements require substantial mass (e.g. 1996 Mars Pathfinder 5 kg rover, 1 kg science mass compared to the 2011 MSL 930 kg rover, 80 kg science mass). Because Mars is relatively close and scientifically interesting, the move is now away from capable field laboratories and toward sample return to Earth. This is also reflected by the desire for a comet sample return mission. A consequence of this new emphasis will be that a few objects will be very well understood by bringing samples to Earth, but our reconnaissance of the broader small body population, especially the distant primitive objects will not keep pace. This is partially a practical issue since solar power is only available for inner Solar System missions. Reliable deep-space power and propulsion (Spacecraft Systems section) need development to enable transportation of science packages to distant small bodies, and this is occurring slowly in the present era.

The Rosetta orbiter and its Philae lander, launched in 2004, will explore the comet 67P/Churyumov-Gerasimenko starting in 2014 for nearly 18 months [19]. The comet's orbit runs from 1.3 to 5.7 AU. The science instruments on the orbiter and lander are representative of what will be required at any small body in our system or at a distant star system. This is a solar powered craft and will rendezvous with the comet at about 3 AU on its inward orbital leg. It uses chemical propulsion and gravity assist maneuvers to reach the comet, which is why the mission is so long. The vehicle is large with a mass of 3000 kg and over half is chemical propellant. Only 7 percent of the vehicle mass is instrument mass. The orbiter has 11 instruments making up a mass of 170 kg. The lander mass is 110 kg of which 27 kg are the 10 instruments. Tables 1 and 2 describe the instruments on the orbiter and lander. Notice the orbiter emphasis is on basic comet morphology, composition, and physical properties while the molecular analysis and chemistry capabilities are on the lander. The latter topics are extremely difficult to address unambiguously with a few in-situ instruments. If there were primitive life just below the comet surface, we would probably not recognize it. Such an inquiry takes significant resources. Nearly 40 years after the Viking missions to search for life on Mars, we are still not sure how to ask definitive questions about local biochemistry and receive an unequivocal answer at the object in real time.

Table 1: Scientific instruments on the Rosetta orbiter [19].

ORBITER Instrument Type	Wavelength	Science Objective	Object Component
Imager	Visible	Morphology Composition	Nucleus Surface Gas + Dust
Imaging Spectrometer(2)	UV Visible+NIR	Composition Mineralogy	Gas + Dust Surface
Microwave sounder	GHz	Composition Physical properties	Gas Surface
Radio science (commun. antenna)	3 and 11 GHz	Physical properties	Nucleus
Radio sounder	MHz	Internal structure	Nucleus
Mass spectrometer(2) (w/ ion beam evap.)		Composition Physical properties	Gas Dust grains
Atomic force microscope		Physical properties	Dust grains
Grain impact analyzer		Physical properties	Dust grains
Magnetometer Plasma analyzer		Physical properties	Nucleus plasma

The sampling and analysis campaign of the Rosetta Philae lander is a one-time event on the comet surface. The operation is sophisticated for the instrument mass delivered to the comet surface. It involves a coordinated program of several instruments operating synchronously to measure the morphology and elemental and molecular composition of material brought up from 30 cm below the surface. This is prototypical of the surface operation that will occur in the exploration of small bodies at other stars. The sequence involves pre-imaging of the chosen sampling site, color imaging of the sampling area (to determine surface structure, grain morphology and composition), drilling a hole and extracting a core sample, delivering this sample (few cubic mm) to an oven, rotating the oven to the analysis port, imaging the oven sample (for grain morphology), performing spectroscopy of the oven sample (for composition), a controlled heating of the sample to release volatiles, distribution of the gas to analyzers, performing gas chromatography and mass spectroscopy of volatiles (elemental and molecular composition, light elements, isotopy, chirality of compounds), and finally doing a post-sampling color imaging of the sampling area plus an optional alpha/x-ray spectroscopic (APXS) analysis for elemental composition.

Table 2: Scientific instruments on the Rosetta Philae lander [19].

LANDER Instrument Type	Wavelength	Science Objective	Object Component
Imager Microscope Spectrometer	Visible IR	Morphology Composition	Regolith
Microscope	Visible	Morphology Mineralogy	Regolith
Radio sounder	MHz	Internal structure	Nucleus
Alpha & x-ray spectrometer		Elemental composition	Solids
Gas chromatograph Mass spectrometer (first unit)		Elements Molecules Chirality of compounds	Volatiles Astro-chemistry and biology
Slide hammer, Thermo-probe		Mechanical Thermal prop.	Surface, 30 cm
Gas chromatograph Mass spectrometer (second unit)		Light elements Molecules Isotopy	Volatiles
Magnetometer Plasma analyzer		Magnetic prop. Physical prop. Composition	Surface Plasma
Drill, sampler, oven		Mech. prop. sample coll. and heating	Surface, 30 cm
Acoustic sensor Impact sensor Electrostatic sens.		Mechanical Physical Electric prop.	Surface Dust grains

The limitations of devices and lack of certain capabilities for scientific instruments in our Solar System is motivating research that will benefit future interstellar exploration. The use of imagers and spectrometers at dark, distant objects may require active illumination at many different spectral bands using efficient diodes. There is a need for compact, lightweight alpha, neutron, and x-ray generators for back scattering, penetrating radar to glean internal structure of objects, compact in-situ sample analysis packages which are reusable, and sophisticated down-hole analysis technology. In-situ studies require a Raman microscope for mineralogy, light-weight imaging electron microscope for elemental analysis, and reliable lightweight, lasers for evaporation of dust grain and surface regolith (shifting away from the ion sputter evaporator used on Rosetta as too complex). Laser induced breakdown spectroscopy (LIBS) in vacuum combined with Raman spectroscopy for millimeter-surface spots at 1 to 10 meter distances from the lander can open huge areas around a landing site to composition studies. The capabilities for in-situ analysis would be significantly expanded by micro-scale sample mapping with x-ray excitation from miniature, tunable x-ray sources, capillary focusing optics, and wide spectral range detectors. Sample introduction to a mass spectrometer by laser desorption ionization, MEMS-based gas chromatography, and tunable IR laser spectrometers at 3-5 microns are all needed to expand the search for complex hydrocarbons, possible signs of biochemistry, and determine isotopic ratios.

5. Summary

We have reviewed the emerging technologies discussed at the SBAG4 Technology Forum on Small Body Scientific Exploration and suggested innovations needed to enable autonomous robotic explorers for future interstellar missions. The technologies developed to address small body and outer planet exploration will form much of the technical basis for designing interstellar robotic explorers. There are technological and design considerations that cut across the different systems, including artificial intelligence to make decisions and adapt to the unexpected, independent operation of the automated team with no human intervention for decades, and robotic governance of the exploration program. The many smaller robotic explorers will need to be autonomous for several days at a time between instruction updates from the parent craft. With only a finite number of robotic vehicles available to explore the many celestial objects, the spacecraft must be capable of reuse, repair, and reprogramming if the science campaign is to have any longevity. The vehicles will have to be reconfigurable to meet the different mission needs, which cannot be predicted ahead of time. This leads to the innovation of plug-and-play spacecraft with interchangeable parts built around generic hubs choices (flyby, orbiter, lander). Miniaturization of spacecraft components reduces propulsion demands and puts more science onboard for a fixed mass budget. Future robotic vehicles must also be capable of refueling with consumables, like propellant, since this usually limits the lifetime more than hardware. For any long-term robotic presence at the star, consumables can only be found in-situ, so there is a need for robotic mining and refining of ice, liquids and other chemical feedstock.

The need for flybys, rendezvous, and touch-and-go at multiple small bodies over large tracts of a star system implies long-life electric propulsion that uses propellant efficiently. The weak gravity fields of small bodies make solar and radioisotope electric propulsion ideal for these missions. Solar cells for electricity are limited to regions of reliable illumination and otherwise nuclear/radioisotope generators are required. Long-life radioisotopes either have to be taken on the interstellar voyage, extracted and processed in-situ, or produced from a nuclear breeder reactor. For flyby and rendezvous missions in the inner star system where light or plasma wind are abundant, solar or magnetic sails would eliminate the need for propellant, but these technologies are not yet developed. Fully integrated six-degree of freedom GNC is needed for autonomous in-space operations around any body. A key development for event recognition and automated data taking is the integration of a wide range of possible event responses with the onboard GNC to coordinate the science instruments with the motion of the vehicle. Sophisticated command and sequencing software will form the instruction base for the robotic explorers. The software will be programmable by the local coordinating AI, not humans, and this is a capability we do not have today. A key advance needed in our Solar System for command and sequencing is distributed, coordinated decision-making that is reactive, makes real-time choices, has fault-detection and response, and has re-planning capability. This will pave the way for AI on deep-space missions capable of initiating unplanned activities based on field discoveries.

There are major advances required for both remote and in-situ science instrumentation, and these will benefit science here as well as at distant stars. The important capability to measure atomic compositions during a flyby with active gamma and x-ray instruments is missing today. Prior to landing at any potentially life-bearing body, remote sensing for biochemical and life signs will be critical from orbit. Sampling and in-situ analysis technologies are the most underdeveloped today. Deep coring, down-hole in-situ analysis, and smart sampling systems to choose material are technologies missing today and will be essential in our Solar System and at other stars. In-situ analysis packages that are reusable and not limited to a single measurement cycle will be needed especially for surface visits to multiple locations on one body. For detailed mineral, chemical, and biological analyses there is a need for either sophisticated in-situ analysis packages at the landing site or sample return to an in-space, robotic chemistry lab.

We have certainly not identified all the innovations needed for autonomous robotic explorers at other stars. The important message is that all the robotic technologies for star exploration will have to first be perfected in our own Solar System, including full autonomy and AI, and in fact will be used here to do science. If a fully independent robotic system cannot do good science without human intervention in our Solar System, why would we trust it to do this job light years away? This is a different perspective than the one of an autonomous robot being a simple extension of our human presence at a remote location. It is a ceding of some degree of control and originality to an intelligent machine that is supposed to send us data based on research it carries out independently. How do we take advantage of this to do exceptional science in collaboration with machines? AI will determine its own path and come to its own scientific conclusions at the star and do this long before we will know about it. Within the constraints of light-speed communication, this is what robotic science becomes as our technology takes it farther from Earth.

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