Robotics Technology for In Situ Mobility and Sampling

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Mobility System Concepts

Mars rotorcraft

*4-wheel
drive/steer rover*

*Tethered descent of lunar
pit or any steep slope*

*Venus variable
altitude balloon*

The mission concepts described in this document are pre-decisional and are provide for planning and discussion only. The re-search was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

1. Introduction

Robotic in situ mobility systems enable science by providing wide-ranging access to planetary surfaces and subsurface voids (pits, caves, and crevasses), while robotic instrument deployment and sampling systems enable science operations in diverse, poorly known conditions with very limited communication with Earth. The past decade saw major progress in surface rover capability, breakthroughs in rotary-wing aerial mobility, promising innovations in variable-altitude balloon technology, a viable mission concept to descend a pit on the Moon, and many innovations in sampling systems. This white paper synthesizes a cross-cutting view of how recent progress in robotics can contribute to missions in the 2023-2032 decade and where further key technology development can impact the 2033-2042 decade, with cross-references to science white papers (WP) and Planetary Mission Concept Studies (PMCS) that motivate the robotics capabilities. The discussion is organized in subtopics covering surface mobility, subsurface void mobility, aerial mobility, instrument placement and sampling, and cross-cutting component technologies. Several closely related or complementary topics are covered in other white papers, including advanced EDL, system-level autonomy, and deep subsurface access [Carson WP, Day WP, Edwards WP, Schmidt WP].

Significant cross-cutting benefits exist in promising new robotics technologies that can enable or enhance mission concepts for very long range rovers for the Moon and Mars, rovers for high latitudes on the Moon and Mars, descending pits and crevasses on the Moon, Mars, and Enceladus, and variable altitude balloons and rotary wing aerial mobility for Venus, Mars, and Titan. Needs and promising solutions exist for robot arms that do not require preheating, rock and ice penetration and analysis on the Moon, Mars, and Ocean Worlds, science operations with much less ground-in-the-loop interaction, and avionics miniaturization, performance enhancement, and cost reduction. Funding for maturation of cross-cutting robotics technology is needed to maximize these benefits.

2. Surface Mobility

Surface mobility provides access to science targets not reachable from a static lander. On Mars, rovers to date have been limited to fairly benign terrain, driving 3 to 4 hours per day and a few 10s of kilometers in the life of a mission, with solar-powered rovers limited to low latitudes. The past decade has revealed that Mars is very diverse, and there is a need to access a much greater range of that diversity to understand its habitability, geology, and climate history [Jakosky WP]. This requires access to widely separated sites [Horgan WP], to a wide range of latitudes, including mid-latitude [Bramson WP] and polar sites [Smith WP, Becerra WP], and to a wide variety of terrain, including steep slopes [Dundas WP]. The Moon is also diverse, with widely separated science targets. The “Intrepid” PMCS has defined a rover mission with a low latitude traverse of ~ 1,800 km in 4 years [Robinson PMCS]. Lunar rovers are also needed to map volatiles at the poles [Cohen WP], which requires operation in permanently shadowed regions. In situ geochronology is also a desired mission for the Moon or Mars [Cohen PMCS]. This would be most valuable with samples from two widely separated sites, but it requires a very heavy payload that would be expensive to transport; a fast, low-cost rover that brought samples to instruments on the lander may be an alternate architecture. A rover might also contribute to future lunar sample return [Valencia WP]. Science at other bodies would also benefit from access to multiple surface locations [Castillo-Rogez 2012].

Considerable progress has been made in the last decade toward improved surface mobility for Mars and the Moon. Motivated initially by access to recurring slope lineae (RSLs) on Mars, tethered vehicles have been demonstrated for accessing steep slopes by rappelling down from the top [Nesnas 2012]. Such concepts are relevant to Mars, the Moon, and steep slopes on icy moons, as well as to pits on the Moon and Mars (see Section 2). Surface mobility studies for future Moon and Mars missions predict improved mobility using fewer actuators in a four-wheeled architecture with all-wheel drive/steer and large, compliant mesh wheels that stow in a smaller volume for interplanetary cruise [Robinson PMCS, Muirhead WP]. This mobility architecture may be a model for reducing the cost of science rovers for future missions. The Intrepid study shows that very long-range surface mobility on the Moon is possible, with driving speeds up to 30 cm/s ($\sim 5\times$ more than demonstrated on Mars to date), given readily achievable advances in onboard autonomy to reduce the frequency of unplanned stops and to maintain absolute position knowledge of the rover.

The Intrepid concept for the Moon raises questions of how much range might be possible for rovers on Mars in the future and what science benefits might accrue. Mid-TRL work exists toward long-lived, dry-lubricated actuators that could operate without preheating at all latitudes on Mars and the Moon [Hofmann 2016], while supporting driving speeds comparable to the Intrepid concept. This would be enabling for a wide range of new rover mission concepts. Dramatic miniaturization and performance improvements of onboard computing architectures, navigation sensors, and communications systems is possible in the coming decade (Section 6). With this, Mars rovers for low to middle latitudes are plausible that could traverse somewhere between 100 and many hundred kilometers in a few Earth years. This could open up possibilities to explore substantial Martian diversity in a single New Frontiers-class mission. For polar regions, this might lead to a rover that could sample many kilometers of layered terrain in a single Martian summer.

Small, low-cost rovers are in development for the Moon and Mars [Tallaksen 2017]. Other types of surface mobility systems in development include mechanical hoppers for small bodies [Hockman 2016], limbed systems for extreme terrain [Reid 2019], and extreme temperature, predominantly mechanical rovers for Venus [Sauder 2020].

3. Subsurface Void Mobility

Subsurface voids are of interest for their potential relevance to astrobiology, potential records of geology and climate, and for the Moon and Mars, as potential habitat locations for eventual human explorers. Many pits that appear to be openings into lava tubes exist on the Moon and Mars, vents that link to a subsurface ocean exist on Enceladus, and many other bodies have landscapes with potential to contain caves or crevasses [Titus WP].

Exploring pits on the Moon and Mars can be approached with rappelling rovers similar to the two-wheeled Axel or the four-wheeled DuAxel vehicles that have been developed for descending steep slopes on Mars. A proposal was submitted to the 2019 Discovery mission solicitation to explore a lunar pit with this approach, using precision landing near the pit and a two-wheeled vehicle that would egress from the lander and descend the pit on a tether [Nesnas 2019]. A similar approach is conceivable for Mars, though constrained to elevations low enough that landers can decelerate adequately in the thin Martian atmosphere and affected by the performance of precision landing systems for Mars. Synergies between steep terrain access and pit access may give multiple uses to further development of rappelling vehicles. Other vehicles have been prototyped for planetary cave exploration, including limbed wall-crawlers that use microspines or other forms of attachment, small rough terrain ground vehicles that might explore horizontal

reaches of caves, and rotorcraft for bodies with atmospheres [Blank WP]. There may be synergies between some of these concepts and vehicles for surface mobility on small bodies or icy moons.

Investigating the prebiotic chemistry and potential habitability of Ocean Worlds is a very high priority. For Enceladus, this includes the possibility of mobility systems that would reach and descend a crevasse toward the subsurface ocean [Schmidt WP]. Mission architecture and mobility system concepts for this are in development [Ono 2016, Carpenter WP].

4. Aerial mobility

Aerial mobility is applicable to Venus, Mars, and Titan, and includes buoyant and heavier-than-air vehicles. The high-density Venusian atmosphere is well suited to aerial mobility; the middle cloud layer centered around a 55-km altitude features an Earth-like temperature (30 °C) and high-speed (70 m/s) ground-relative winds that carry balloons around the planet in 4–5 days. This is a highly energy-efficient mobility architecture that achieves planet-wide access with no energy expenditure for lift. Key science questions remain about Venus that can best be addressed with an aerial platform operating in the middle atmosphere [Gilmore PMCS, Izenberg WP, Cutts WP]. Recent evaluation of the many types of aerial vehicles [Cutts 2018] concluded that variable altitude balloons (aerobots) [Hall 2019] should be developed to carry larger payload modules compared to the VEGA balloons (50–100 kg vs. 7 kg) and for longer durations (1+ months vs. 2 days). This conclusion was inspired in part by recent terrestrial developments in similar vehicles (e.g., Google Loon) that could be adapted for Venus. Aerial exploration below the Venusian clouds is achievable in principle, but requires development of aerobot and payload systems that can tolerate the high atmospheric temperatures [Cutts WP-VeCaTEx].

Balloon and fixed wing aerial vehicles were studied for many years for Mars, but have not flown. Some scientific questions still would benefit from the long-range mobility that such platforms offer, such as low altitude measurements of crustal remanent magnetism [Raymond 2001, Mittelholz WP]. The 2020 Mars Perseverance rover will also deliver Ingenuity, a 1.8 kg coaxial helicopter with 1.2 m diameter rotors, as a technology demonstration of the first planetary rotorcraft [Balam 2018]. This vehicle was initially inspired by potential use as a scout for rovers, which remains a relevant application. Scalability studies suggest that a 5 kg helicopter with an improved rotor design and the same rotor diameter could carry ~ 1 kg of payload and that a 30 kg hexacopter could carry ~ 5 kg of payload, both with flight ranges of ~ 5 km/sol [Johnson 2020, Bapst WP], which creates possibilities for revolutionary science missions using such platforms [Bapst WP, Mittelholz WP, Rapin WP, Lin WP]. This requires further technology development on autonomous safe landing, autonomous safe flight over arbitrarily sloped terrain, and flight-qualified avionics components with very low size, weight, and power (SWaP).

A variety of buoyant and heavier-than-air aerial vehicles have also been studied for the dense atmosphere and low gravity of Titan. The Dragonfly concept selected for the New Frontiers 4 mission is an ~ 400 kg octocopter, planned for launch in 2026, to explore several hundred kilometers in ~ 2 years, progressing from an equatorial landing in a dune field toward a large impact crater [Lorenz 2018]. High priority Titan science objectives for the coming decade emphasize orbiter-based science, as well as in situ exploration of polar regions and sampling of the high latitude seas [MacKenzie WP]. This might be addressed by a flagship orbiter that also releases one or two probes targeting seas [Nixon WP]; alternatively, future in situ aerial vehicle missions might include such objectives. In addition to Dragonfly-like vehicles, in principle a variable-altitude aerobot deployed at high latitude could descend to sample Titan's liquids and sediments, as well as circumnavigate the entire moon to observe more of Titan's diversity at high

resolution. Additional aerial system concepts that could be matured for the decade of the 2030s or beyond include various designs for small, heavier-than-air aerial daughtercraft paired with a lander or larger aerial vehicle mothership [Uehara 2019]. Precision landing on Titan with gliding decelerators is also plausible for future in situ missions [Matthies 2020, Schutte 2020], especially following an orbiter mission that provides improved global mapping imagery [Barnes WP].

5. Instrument Placement and Sampling

Missions have flown using robot arms with 3, 4, or 5 degrees of freedom for instrument placement and/or sample acquisition; examples include Mars rovers (5-DOF), Mars landers (4-DOF), and OSIRIS-REx (3-DOF). Deployment mechanisms with fewer DOFs are also used, such as for drills. Drills in the 10 cm depth class have flown (e.g. on MSL) and several 1 to 2 meter-class drills are close to flight (e.g. for the Rosalind Franklin and VIPER rovers). Pneumatic sample transfer systems for loose materials are becoming common [Bierhaus 2018, Zacny 2019]. Future mission needs for instrument deployment and sampling systems include operating at colder and hotter temperature extremes, operating with more autonomy, sampling a wider range of materials, and the perennial need for miniaturization.

Progress for colder environments includes the COLDArm manipulator under development for lunar surface mission, which reduces the need for preheaters through the use of bulk metallic glass (BMG) gears [Hofmann 2016] and cold-survivable motor drivers [Hunter 2018]. This will benefit missions to all cold environments. For the hot extreme, drilling and pneumatic sample transfer for Venus landers has been addressed in the HOTTech program [Zacny 2017].

A Europa lander would require highly autonomous landed operations, due to the short mission lifetime, very limited downlink bandwidth capability, long latency for ground-in-the-loop (GITL) command cycles, and high likelihood of radiation-induced soft errors that would require onboard detection and recovery [Reeves WP]. Providing such autonomy requires advances in onboard perception and planning capabilities to understand the local environment, the state of the spacecraft, the outcome of each action, and to plan further actions. Very long-distance rover missions on the Moon are much less constrained than Europa, but will benefit from similar advances in autonomy for instrument placement to maintain rapid progress with minimal GITL cycles [Robinson PMCS]. Progress for these scenarios will benefit other future missions.

Work is in progress on methods for sampling icy materials on Ocean Worlds at the surface on Enceladus [MacKenzie PMCS, Choukroun WP] and in the shallow subsurface (> 10 cm) on Europa [Dooley 2019]. Related needs exist to gain insight into climate history on Mars by studying ice layers in Mars' polar layered deposits (PLD) [Becerra WP]. Although Mars PLD science goals start with fairly shallow coring (50 cm), ultimately sampling 500 m of layers would give insight into 1 Myr of Mars climate variations [Smith 2020]. This could be achieved by a lander with a deep drill or by a rover with a very shallow drill, if the rover could drive over and sample enough exposed layers in one Martian summer. Sampling subsurface liquids is envisioned as part of long-term exploration of Ocean Worlds and Martian aquifers [Schmidt WP, Edwards WP]. Sampling Titan's surface liquids and sea bottom sediments may someday be done with a probe delivered with an orbiter [Nixon WP]; it could also be done by an in situ mobility system.

Improved control software that takes into account the flexibility and load capacity of robot arms would allow substantial reduction in structural mass while maintaining positional accuracy. Techniques to reduce the mass and volume of wire harnesses, including wireless communication, would also benefit robotic arms. Concepts for Mars rotorcraft missions [Bapst WP] raise needs for very lightweight mechanisms for instruments (e.g. camera gimbals) and sampling devices.

Several sampling technologies are being developed for lunar exploration and In Situ Resource Utilization (ISRU). One example is the 1 meter TRIDENT drill, which is based on the Icebreaker drill developed for a Mars mission concept [Zacny 2013]. Another is the Planetary Volatiles Extractor (PVE_x), which designed for delivering volatiles from 1 m depth to either a GCMS or a ColdTrap for ISRU, and which can provide core samples for in-situ analysis or sample return [Zacny 2016].

6. Cross-Cutting Component Technologies

For actuation, there has been substantial progress in miniaturization of brushless DC motor controllers for space applications [Hunter 2018]. Work in progress on BMG and dry film lubricated gears and bearings is expected to enable heaterless actuators for mobility and manipulation systems [Hofmann 2016].

For sensing, mobility and manipulation operations require progress in small 3-D perception sensors to operate in the dark and in extremely cold or high-radiation environments. High performance, space-qualified IMUs currently have mass of several kilograms. Miniaturization of IMUs is progressing for demanding Earth-based applications, yielding near-navigation-grade performance in much lighter sensors; space qualification of such IMUs would be valuable.

For computing, FPGA-based coprocessors have enabled onboard vision systems for faster rovers and for safe and precise landing, but higher performance with lower SWaP is needed. NASA's High Performance Space Computing program targets a huge leap in general purpose computing capability with multi-core processors developed with radiation-hard-by-design techniques. Increased use of COTS-based electronics is also an attractive possibility [LaBel 2018, Zucherman 2018], potentially leveraging highly fault-tolerant automotive or medical-grade products to cope with radiation-induced soft errors.

Reducing the frequency of ground-in-the-loop command cycles will be essential for a long-range lunar geology rover and a Europa Lander, and will benefit most missions. This requires more onboard autonomy to provide better situational awareness and more sophisticated behavior planning, execution monitoring, and fault recovery.

Solar array size and battery mass, volume, current limits, and temperature limits are significant design constraints for mobility systems. Investment to bring promising new power/energy technologies to maturity would significantly benefit mobility systems [Bugga WP].

7. Summary

Surface mobility: In the coming decade, advances in autonomy can enable lunar rovers for low latitude missions that traverse hundreds of kilometers per Earth year. Progress on high-speed, heaterless actuators and higher performance onboard computing could enhance lunar rovers for all latitudes and may enable Mars rovers with range an order of magnitude greater than missions to date, as well as enable solar-powered Mars rovers to high latitudes. Tethered rovers for steep slopes are possible now.

Subsurface mobility: Tethered rovers can descend pits and rotorcraft could do so on Mars in the future, especially with precision landing near the pit. Many pits on Mars are at high elevations, where ability to land or fly is a limitation. Accessing horizontal cave passages is possible now with robots on Earth, but requires development for other bodies. Mobility systems to descend vents on Ocean Worlds are in development.

Aerial mobility: Fixed-altitude balloons may be valuable for crustal magnetism studies on Mars. Variable-altitude balloons are promising for operation in the middle atmosphere on Venus,

including the possibility of dipping below the clouds to image the surface on the night side, and may have applicability on Titan, for example if they could both access the surface and circumnavigate Titan at high latitudes. Planetary rotorcraft will debut in 2021 as a technology demonstration on Mars and were selected for a New Frontiers mission to Titan. Advances in avionics, autonomy, and instruments could open up compelling new mission concepts for rotorcraft at Mars and Titan.

Instrument placement and sampling: Heaterless actuators will improve operability of robot arms in cold environments. Advances in arm control software and autonomy could enable significant structural mass reduction and greatly increase science productivity. Sampling surface and shallow subsurface ice and accessing greater depths in rock and ice are overlapping needs for the Moon, Mars, and Ocean Worlds.

Cross-cutting component technologies: Substantial further progress is possible in the coming decade in several areas, including much smaller IMUs, cameras and LIDARs for dark and extremely cold environments, better batteries, and much higher performance computing systems. Leveraging progress for commercial and defense applications is promising in these areas.

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