Robot Technology Advancements for In-Situ Exploration of Subsurface Environments

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Brief Background of Planetary Exploration

In the earliest period of planetary exploration, flyby missions were built and sent out to explore our planetary neighbors. The Mariner spacecraft series was the robotic workhorse for planetary scientists for these early flyby missions: Mariner 4 launched in 1964 and sent to Mars; Mariner 5 launched in 1967 and sent to Venus; Mariner 10 launched in 1973 and sent to Mercury. The spacecraft technology improved and extended our study to the outer planets with Voyager 1 & 2. They were launched in the 1970s and performed the Grand Tour mission by performing flybys of Saturn, Jupiter, Uranus, and Neptune. These flyby missions gave scientists data on atmospheric and surface characteristics of the planets. Eventually, scientists needed better reconnaissance platforms to study planetary geography characteristics and weather/atmospheric characteristics over time and embarked upon orbiting missions. Some well-known orbiting missions include Magellan at Venus and Galileo at Jupiter.

The need to study the planetary surface directly became key for life detection exploration and determining the environmental characteristics for life to exist on other planets. Mars is a well-known target for lander missions such as Viking to see if life was present. The landing missions gave way to the rover missions. Those notable missions include Mars Pathfinder, the Mars Exploration Rovers, and the Mars Science Laboratory with a task to “follow the water”, a key component for the existence of life. Mars and Titan will soon be visited by autonomous drones. As Entry, Descent, and Landing technology becomes more mature, planetary science missions increase in variability and enable innovation in the next leg of the journey: exploring beneath planetary surfaces.

Each scientific and technological step was built upon the knowledge of the prior missions. Each successive mission sought for greater detail of the planetary environments. This ultimately brings robotic exploration platforms and tools into direct contact of the environments to be studied as if the scientist was present on the surface. Instead of observing a planetary surface indirectly at a superficial level, planetary surface robots may make observations beyond the opacity of the surface by interacting with the environment. This white paper hopes to illuminate the science motivation for exploring subsurface environments, the types of subsurface environments worth exploring, and the future of robotic technology to achieve these subsurface science objectives.

Motivation for Subsurface Environments

As planetary exploration has evolved over the decades, robotic technology has improved the reach of science investigators into various planetary environments such as orbital, atmospheric, and surfaces. Now that investigators have robotically accessed the planetary surface by way of landers and rovers, there is now a shift to gain access beyond what is seen at the surface. The shift is motivated by the realization that much of our surface observed data has been affected by weathering conditions. Conditions, such as wind or precipitants, that will alter the chemistry and structure of a planetary surface over time. Science investigators want to examine unaltered environments, thus preserving the historical record of past planetary processes and events. Gaining access to unaltered environments requires technology to penetrate below the surface or to displace surface terrain.

In the push to peel back the layers of a planet and gain access to zones that are difficult to yield data by remote sensing methods, there are basically three zones that subsurface exploration would have better success to study. The three zones are: ices, liquids, and soils. These environments tend to hold information about a planet's geophysical and climatological development over time. The instruments need to be custom made for these subsurface

environments and can be very similar to Earth-based measurement tools. There are Earth analog environments that would make for developmental testbeds for planetary exploration. Technology advances will be needed to access the subsurface, convey instruments, and send the data back for analysis. We will identify subsurface environments, promote robotic technology developments, and offer architectures to enable these unique planetary missions.

Within Liquid Environments

Water is evermore prevalent in our solar system yet the question of why it is so prevalent remains unsolved. Global oceans lie beneath the icy crust of Saturn's moon Enceladus, Jupiter's moon Europa, and, most recently discovered, Ceres. Major geological features (e.g., ridges, chaos terrains) on the surface of Europa suggest possible connections between the crust and the ocean beneath. For instance, the formation of chaos terrain is hypothesized to be linked to the thermal activities of the ocean [1], [2]. Investigations of the properties of the ocean beneath Europa's crust or any subsurface fluid intrusions will dramatically improve our understanding of planetary formation and evolution, and habitability. An in-situ underwater vehicle, ideally autonomous, directly addresses this critical investigation.

The only other planetary object that currently has large stable liquid bodies on its surface other than Earth is Saturn's moon Titan. Titan's large hydrocarbon lakes and seas are an astrobiologically interesting future mission target because the organic molecules photochemically produced in Titan's atmosphere are expected to fall and collect in lakes. There they could react and recombine into molecules thought to be the building blocks and energy sources of life [3]. To date, the lakes of Titan have only been studied via low resolution remotely sensed data from Cassini mission flybys. Thus, many questions remain about how the hundreds of fluid-filled and dry lake basins [4] form and evolve, and whether they are or used to be habitable. An in-situ surface robot or robots with the ability to probe the atmosphere, surface, and liquid bodies is ideal for studying the liquid and its components, the rocks and sediments on the lake floors, and the shores of these lakes.

Subsurface Ice and Soils

Our knowledge about water ice on the Moon was revolutionarily developed in the past decade. In particular, a recent study using orbiter-collected reflectance data confirmed the presence of surface ice in the lunar permanently shaded regions (PSRs) [5]. In addition, strong evidence from epithermal neutron data and crater geomorphology supports the presence of buried ice [6], [7]. However, these analyses are either constrained on the topmost few 100s micron layer (e.g. the reflectance data) or complicated by all sorts of hydrogen bearing species (e.g., the neutron data). There are two unknowns about lunar ice. Although the surface ice has been observed directly, there is a lack of knowledge how water ice distributes in the subsurface on the Moon. Knowing the vertical distribution of water ice is critical for assessing the utilization of these ice as in situ resources, such as rocket fuels, drinking water, and radiation protection. Investigations of subsurface environment in the lunar PSRs are necessary to resolve these questions and will expand our knowledge about lunar water and water ice as well as their dynamics tremendously.

Two major research topics in the lunar community are about water (OH and H₂O) cycles and in situ resource utilization (ISRU) of lunar water. Both types of research need the knowledge of subsurface ice and soils on the Moon. The distribution of subsurface water ice is crucial for economic geologists to assess whether exploring lunar ice is more economic than bringing it from the Earth in the future lunar exploration. It is also critical for revealing the dynamics of water and water ice in the subsurface. Geotechnical properties of water ice and regolith on the Moon are key

information for future exploration of the Moon, such as lunar base development and ISRU of lunar water. The geochemistry in rock layers could be studied to find a historical presence and distribution of water on a planet. “Following the water” paradigm also helps to learn about planetary climatology. Water can be a significant component in planetary formation. The presence of water either shapes the geography or affects the soil chemistry. Subsurface exploration for hydrated salts, presence of carbonates and precipitates from water chemically mixing with soil will help define how the planet or moon was affected and within those layers find fossils or spores or trapped organic compounds.

Caves

Caves provide protection against hazards such as radiation, temperature fluctuations, and meteorite impacts. They could serve as shelters for temporary or permanent human settlements [8]. Given their large size, they can also be used for storage [9], and resources could be mined through excavation or from nearby volcanic vents. The Moon [10] and Mars is thought to harbor many caves. Skylight entrances and pit crater chains have been observed with cameras on several spacecraft in Mars orbit [11]. The motivation for studying Martian caves is manifold. Cave ice may have preserved a record of past climate conditions or evidence of past microbial life. At temperatures typical of the subsurface today, biological molecules, such as nucleic acids and proteins, are well-preserved. Further, caves are protected from radiation and environmental extremes [12]. Since Mars lost most of its magnetosphere, its surface became an inhospitable cold desert exposed to high radiation levels [13]. These surface features possibly harbor biosignatures, but only those of extinct, and not extant life. However, the hydrothermal subsurface conditions observed on early Mars might have presented a more hospitable environment capable of fostering life. Such mirror areas on Earth are considered the most ancient habitats where life could have emerged. Therefore, it remains prudent to explore subsurface areas on Mars while searching for life there [14]. Martian caves are excellent preservers and sources of potential biosignatures.

Technologies to Access Subsurface Environments

There has been great success in remote sensing methods, but to study unaltered environments will require in-situ sensing methods. To gain a comparison study of planetary processes, scientists will need to apply Earth science investigation methods to other worlds. These methods may employ digging, swimming, and flying through soils, liquids, and gases. The key is packaging instruments in-situ, getting to scientific destinations of interest, and sending the data back to investigators. This is like scientists on Earth in the field drilling for soil samples, cutting ice cores, syphoning water samples, or capturing aerosols. The new age of planetary study will be interrogating subsurface environments on other worlds and comparing that data with our own Earth to understand the planetary processes. Technology for subsurface manipulation and mobility must be advanced for soil, ice, and liquid environments.

Robotic Manipulators to Expose Subsurface Soils or Ice

Current sub-soil environments are accessed by singular robots using rotary drills, percussive drills, and preliminary puncture or piercing probes. As these options are externally facing, the drill bits risk jamming up or fracturing against harsh material. A larger expanse of manipulability options should be developed to suit the environment, such as cups or shovels for fine grains (Phoenix), drills for solid rock (MSL), grappling for boulders. An unintentional method of manipulating the environment stemmed from a mechanical failure in Spirit’s right-front wheel, dragging the wheel and exposing subsurface white deposits of silica. By creating different, new

techniques for manipulating the environment for subsurface investigations, we will have a variety of specific tools best suited for different materials.

To still interact with the environment with no exposed actuators at the contact point, a robot may dislodge rocks with a prying end-effector, grip objects and displace them, wrap a tether around and pull an object. Additionally, the **actuation method** should shift away from dynamic external interaction to **internal interaction**. Internal

Figure 1: Soft robotic arm demonstrating manipulation. Credit: Steltz

actuation methods include reaction wheels and control moment gyroscopes to offer moments onto the spacecraft body [15] or manipulator. Innovative methods not yet demonstrated in space are soft grippers or manipulators. These technologies also do not have external actuators or even rigid links. Instead of relying on angular momentum, these technologies rely on jamming granular media within a soft sleeve or sack [16], [17]. This media could even be extraterrestrial regolith! There exist many innovative methods that mechanically leverage the geometry, relative mass, and direction of forces or moments without exposed, at-risk mechanisms. The proposed manipulators promote longer mission lifetime and higher adaptability to a variety of object geometries.

Climbing and Rappelling Robots

Science campaigns conducted in subsurface pits and voids benefit from the ability to deliver large payloads to the walls and ceilings of pits and caverns, take long-duration measurements, and remain in constant communication. These tasks require sufficiently sized and powered robots that can access these extreme terrains. Tethered rappelling rovers [18], [19] are capable of carrying large payloads and accessing vertical surfaces below the initial landing point. This makes them ideal platforms for missions that are targeting environments such as cliffs, crevasses, and pits. Climbing rovers [20] can access the vertical walls and ceilings of caverns from below at the cost of increased complexity and actuator mass. These robots move towards accessing the most inaccessible places in planetary exploration.

Exploration of Soil, Ice, and Liquids

Planetary surface explorers span rovers [21] and landers [22], with proposals of hoppers [23], submersibles [24], underwater rovers [25], and rotorcrafts [26]. Of these specialized planetary surface robots, none can explore all three, surface media. We are discovering more and more planetary bodies that happen to have subsurface activity, such as circulating oceans and cryovolcanoes, at a faster rate than we can send planetary surface robots. Outside the moon and Mars, we realistically only send one surface robot to each celestial body every few decades or ever at all. We encourage the development of robots that can survive and sample environments of different material phases, specifically underwater. With this augmented ability, we may speak about planetary surface exploration in terms of three-dimensional space, volume coverage, instead of two-dimensional space, surface area coverage. Dragonfly and Ingenuity are prime examples of breaking the surface constraint but only focus on above surface exploration, focused on extending

travel into the atmosphere. We challenge the community to create robots that can move the entire robot chassis from surface terrain into the hard, icy regolith or through ice sheets and further transition into frigid waters.

Cooperative Robots

All mobile robots sent to extraterrestrial surfaces are designed to function independently: Lunokhods, Marsokhod, Mars Science Laboratories, Mars Exploration Rovers, and Yutis [21]. These robots do not interact with each other. Due to their design, their missions and science investigations are limited in scope despite the complexity of each rover's design. A metaphor may be made to a single ant that is unable to cross an air gap, yet a homogeneous group of ants operating under very simple rules may construct a bridge to enable all the ants to cross the air gap, depicted in Figure 2: Ants utilize each other's bodies to bridge a gap, Figure 2 [27]. Clearly, new capabilities are enabled with multiple cooperating agents in traversing extreme terrain. Cooperative space robotics is a burgeoning field for which categories of cooperative robots exploring planetary surfaces are seen to include: homogeneity vs. heterogeneity, task distribution vs. centralization, environment exploration vs. manipulation, size of group, and simultaneous vs. sequential tasks.

Figure 2: Ants utilize each other's bodies to bridge a gap. Credit: Reid et al.

Figure 3: Free-body diagram of probe and winch manipulating a rock. F_B is the buoyant force. F_T is the tether tension. τ_R is the moment from the momentum control

We propose pursuing techniques that take advantage of cooperative robots to manipulate terrain. A proposed example is a robotic pair joined by a tether and winch. A large wheeled rover may propel a smaller polyhedral probe, then pull the actuated probe as a hook at the end of a line, Figure 3. This technique offers a new solution to the arm or drill, but with no exposed actuators like mentioned before. This type of manipulation is very similar to grappling, which extends to cliff climbing and vehicle towing, Figure 4. The probe is still quite small compared to the conventional rover, which may be leveraged to explore small, enclosed spaces like caves, lava tubes, and skylights. The probe simultaneously acts as an in-situ science platform and source of mechanical leverage. This paradigm shift, or technically mass shift, from one centralized body to a small and large body warrants the exploration of new types of planetary exploration missions, particularly small, enclosed spaces, and sharp topographies.

Figure 4: left, rover catapults probe to elevated ground, probe locomotes around rigid structure; right, probe secures an anchor and rover's winch reels rover up cliff face

Machine Learning for Robotic Exploration

For planetary exploration missions, especially to outer planets, autonomous exploration is necessary. Urmson articulates the requirements and difficulty of controlling robots in extreme

terrain particularly well, paraphrased [28]: Robots operate with only partial knowledge, must safely move at speeds related to dynamics, must account for terrain mechanics, must make decisions quickly for near-continuous motion, must be aware of both local motion constraints and global path planning goals. Traversing extreme terrain, even on Earth, is challenging and dangerous. Due to the extreme terrain, these environments are difficult to access by humans and hard to study. Exploration of extreme terrains is difficult to begin with but even more so if the dynamics of the body and the environment (terramechanics) model are not known *a priori*; predictability of the motion of the robotic system decreases greatly. **Developing algorithms that efficiently sample an environment and learn how to move a robot through an environment in real-time enhances our ability to traverse extreme terrains on outer solar system bodies.**

Integrating Science Data into Decision Making

Currently, human operators intuit the scientific value of exploring specific destinations, much like China's Yutu-2, NASA's Sojourner, and MERs [29]. Although the most recently landed rover MSL shows hints of autonomy, the autonomous interactions are restricted to mobility actions -- separate from any science [30]. The robots exploring the outer planets will very likely face power and thermal limitations dependent on time spent in an extreme environment for which we cannot afford extensive sampling or teleoperators to stop and intuit the next waypoint to visit next. The optimization problem of space exploration is that a limited set of spacecraft resources (power) must be allocated between competing choices (destinations) in a way that maximizes science discovered and mitigates risk, a specific formulation of the multi-armed bandit problem [31]. Reinforcement learning algorithms offer great promise in intelligent sampling processes, especially in applications with no *a priori* knowledge. These learning algorithms should be automated for the safety and efficacy of planetary surface robots.

Learning Robot Dynamics in Unseen Environments

Modeling terramechanics is a large and active field of study. Previous work explores how to model motion through extreme terrains like sand, mud, ice, and how to use the terramechanics to create controllers that can track trajectories effectively. However, these methods assume that the terramechanics are well-known *a priori*. For a planetary surface rover mission, the terrain is uncertain, and the amount of computation and time allocation for intense real-time numerical simulation is not feasible.

In general, we need to learn a dynamics model that encapsulates the interactions between the robot and the environment in real-time and in interpretable form if we are to explore the outer planets. For the model to be interpretable, algorithms should adhere to a mathematical expression, not a black box. Interpretability offers predictability in robot behavior, but also enables scientists to derive planetary science observations from the learned dynamics model. The model must be learned in real-time at a system level, suggesting equations based upon robot state and parameters, not a finite element simulation. To automate mobility control in space, the rover must be embedded with learning and adaptive algorithms as the time delays from long-distance communication do not allow teleoperators to react at appropriate timescales.

For other surface environments, extraterrestrial fluid mechanics models for liquid bodies and atmospheres are less developed than terramechanics models. These dynamic models are specific to robot morphology, which makes this task of learning robot-to-environment dynamics even more daunting but open to improvement. We encourage deploying more robots of various forms, like the SeaGlider and JPL BRUIE, in analogous Earth environments to characterize the predictability of robot motion. We further encourage the development of dynamic models that build in adaptability into the robot's real-time processes.

The dynamics model and control policy are highly coupled models and together, they form an autonomous mobile system. Many similar characteristics for learning the dynamics model of a system are desirable for learning a control policy: adaptability to real-time and interpretability. Whereas learning a dynamics model is a passive process, the control policy is the active component in mobility performance for which safety is a critical obstacle toward adoption. To extend learning algorithms to applications of high consequence, the algorithms should be verifiable, offer safety constraints in real-time, and conform to physical laws. To draw from Lipton's terminology [32], the proposed work focuses on learning the fundamental nature of dynamic systems in time by addressing i) Trust: safety guarantees in the output prediction and algorithm behavior, ii) Causality: deriving relationships between the input and the output, and iii) Information: analyzing the abstraction learned from the neural network and inferring system characteristics from the learned parameters and relationships. We need algorithms that are verifiable or offer algorithm transparency in the way of theoretical guarantees, inference rules [33], and analysis (Lyapunov stability and coefficient stability). Users may apply safety criteria or domain knowledge in the context of constraints, invariant physical quantities, input/output relations, and continuity or bounded sensitivity properties.

Feasibility and Conclusion

The feasibility for subsurface planetary missions is uniquely driven by scientifically desirable target locations. The other cost component is the mission architecture used for exploring target locations. A sample return mission to Earth is more complicated than an in-situ instrument lab. Exploration of icy environments would target comets, permanent icy craters on the Moon, polar ice caps on Mars, and the surfaces and interiors of icy moons of the outer planets. The liquid environments for study include Europa and Titan. The soil environments would include Mars, the Moon, and asteroids. Future subsurface exploration could be supported by NASA's Discovery, New Frontiers, and Flagship class missions, starting from the Moon, to Mars, to comets and asteroids, to the outer planets.

Subsurface exploration is the next logical step for planetary exploration, and an exciting frontier in technology development. This technology will greatly increase our chances of finding evidence of past life (biosignatures) on Mars, Europa, and other bodies. On the Moon and on Near-Earth Asteroids, it will help us discover and access resources, such as water ice, even when they are not present on the very surface.

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