Scientific, Technical, Management Plan

1. Introduction

Rationale. The development and assessment of technologies for penetrating ice and accessing the subsurface liquid water on ocean worlds such as Europa is of great interest to the space exploration community as it will facilitate the detection of evidence of extant life. Our overarching goal in this SESAME technology development effort is to design, realize and validate a prototype robotic cryogenic ice penetration and navigation system.

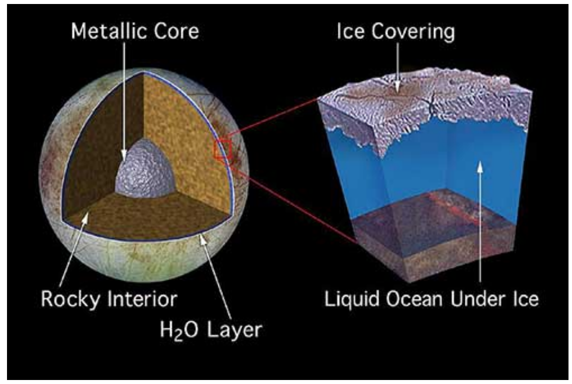

Figure 1: Europa's subsurface liquid ocean. Image Credit: NASA/JPL

Problem Statement. We assert that successful deployment of ice penetration and sample collection systems for ocean worlds like Europa, will require robotic capabilities in order to minimize and mitigate risks involved in such missions because the operations will take place in unknown and dynamic environments. In order to reach liquid water to collect samples, the system will need to navigate through a deep ice sheet (>1km) for during a prolonged mission. What if we were able to develop perception and navigation capabilities for the ice drilling probe to steer around potential hazards or aim towards targets of interest?

Proposed Solution. Within the scope of this project, we will explore the design space for a tetherless, autonomous robotic system (called *TRIDENT*) equipped with a heated rotary drill to penetrate and navigate through the Europan ice, collect scientific samples, and potentially return to the surface at the landing site. We propose to develop and validate three critical subsystems of *TRIDENT*, first individually, and then as an integrated system. These are (1) an ice-displacement system that can penetrate different solid substrates and reform ice behind it; (2) a locomotion system that can drive and steer in solids, liquids, and subsurface voids; and (3) a navigation system that can detect and maneuver around different subsurface regions. The proposed development effort will address the program elements to ensure persistent and efficient progress in penetrating realistic ice profiles by employing an intelligent control method for the *TRIDENT's* drill and locomotion system.

Team and Relevant Work. This interdisciplinary project team, consisting of researchers and domain experts from Northeastern University (NU), Columbia University (CU), and Aeroquatic, has the expertise, connections, and resources to craft holistic solutions for ice penetration and subsurface exploration in unknown environments. The engineering research team (NU, Aeroquatic) has collective expertise in design and validation of field robots including exploration rovers, subsurface water extraction systems, and legged robots; human-supervised robot control; robot perception and motion planning; design and fabrication of robotic mechanisms at micro and macro levels. CU brings a unique expertise in experimentation science investigating material response of planetary materials. This project will strengthen and extend our well-established collaborations among the investigators. In addition to our collective experience in engineering field deployable robots, our team has the domain expertise and technology transfer leadership through our networks. As a result, this team is highly-qualified to translate the proposed research and development effort to a successful technology that will impact the space missions in the future.

Expected Outcomes. Successful completion of this project will provide novel designs and fundamentally sound data that establishes ranges and trade-offs of performance to mature technologies for science missions in order to explore the subterranean oceans to discover the existence of alien life.

1.1. Relevant Background on Europa

In order to achieve scientifically informed engineering design and prototypes, there is a need to understand the properties of Jupiter's icy moon Europa. Europa is important for scientific inquiry for several reasons. One is that its putative global liquid ocean provides astrobiological potential (Hand, 2009). The presence of liquid water and the possibility of geologic reactions providing the necessary chemicals to be exploited by biological systems make Europa one of the most compelling destinations for the search for life. The second important factor about Europa is that it is one of the only other bodies in our solar system to display evidence of ongoing plate tectonics. The lack of impact craters implies a resurfacing process that may resemble plate tectonics on Earth. Morphological evidence of extensional features akin to terrestrial rifting has long been identified (e.g. Helfenstein, 1983; Nimmo, 2004). Transform motion in the form of strike-slip motion and cycloidal features based on wing cracks also observed (Hoppa, 1999; Marshall, 2005). Recent indication of "subsumption bands" provides the previously missing compressional feature (Kattenhorn, 2014). A geologically active icy crust is, however, a double-edged sword in our search for extraterrestrial life: tectonics are needed as a mechanical means of mixing surface oxidants with reductants, a process that is imperative for chemosynthetic life (Chyba, 2000); but tectonics and faulting, which may extend several kilometers into the icy shell, offer technical challenges to any effort devised to burrow through the ice in search of biological markers.

An additional complication is in the form of compositional uncertainties. Analysis from both satellite and land-based infrared spectral data indicates several non-water-ice species on both trailing and leading hemispheres (e.g. McCord, 1998; Fischer, 2015). Hydrated salts, posited to be endogenic, from geophysical processes at the rock-water interface and/or delivered by impacts, have been identified on the leading hemisphere, but an exact match to spectra has not been identified. Based on chondritic abundances and laboratory studies, a short list of various Mg and Na based sulfate hydrates have been suggested (Dalton, 2005). Sulfur ions, believed to be Iogenic, from ionized ejecta from Io implanted on the surface, have been measured on the trailing hemisphere and are considered to be in the form of hydrated sulfuric acid (Carlson, 1999; Fischer, 2015). Although composition can only be assumed for the surface of the ice shell, development of navigation and communication components must consider the possibility of concentrated pockets of these cryominerals at depth.

A third complication offered by the Europan icy shell is temperature. The average surface temperature is ~100K and the temperature at the base of the ice is ~270K (depending on the exact composition). From a materials point of view, this means that the ice is found between 0.36 and 0.99 in homologous temperature (T/Tm) such that mechanical strength and rheology covers the full range of brittle to ductile, thermally-activated deformation behavior. This steep gradient in temperature and therefore mechanical properties means that any descending probe will need to perform at significantly different specifications from the beginning of its journey to the end. A successful probe would need to detect changes and autonomously respond accordingly.

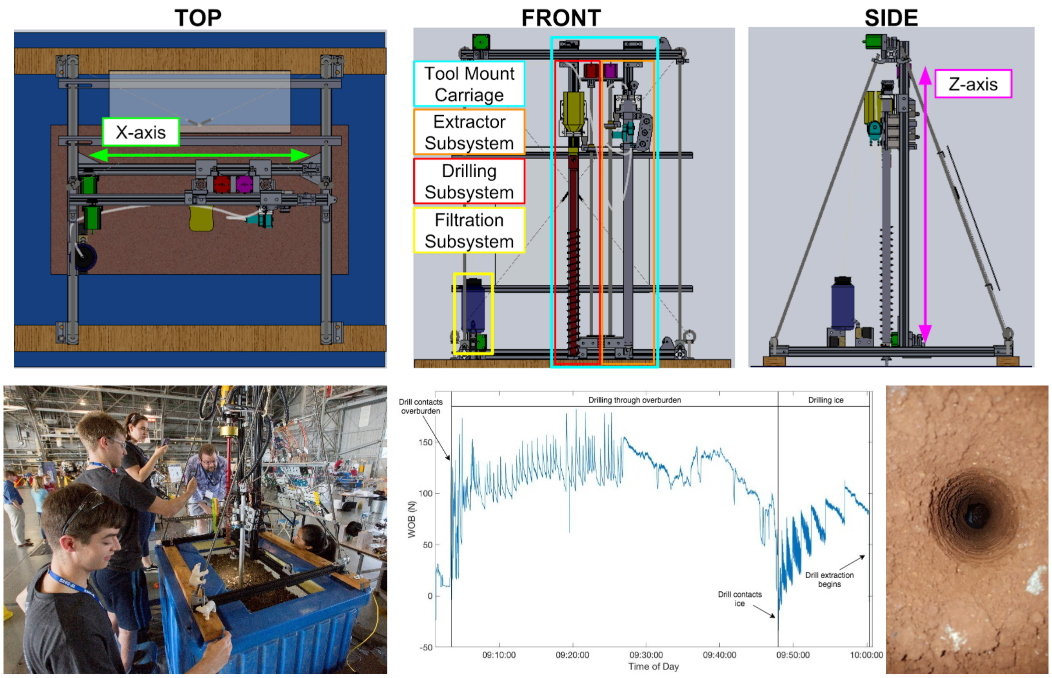

Figure 2: NU-PAWES design features (top); NU-PAWES prototype at the NASA Langley Research Center (bottom-left); Analysis and monitoring of weight-on-bit (N) versus time during the drilling phase (bottom-center); Hole drilled by the system autonomously (with ice block visible) at end of the field test performed at the NASA Langley Research Center in June 2018.

1.2. Relevant Background from the Mars Ice Challenge

Our recent work is highly relevant to the SESAME program elements. In 2017-2018 academic year, six Northeastern undergraduate engineering students advised by PI Padir executed an agile design cycle to realize a multi-stage, stationary, robotic, water extraction system (called *NU-PAWES*) to harvest water from underground ice in a simulated Martian environment. The motivation for this research and development effort was motivated by the merits of in-situ resource utilization (ISRU) for future manned missions to Mars. The team participated in the 2018 NASA Revolutionary Aerospace System Concepts Academic Linkages (RASC-AL) - Mars Ice Challenge. The purpose of the challenge was to maximize water collected within requirements on power, drill weight on the bit, and turbidity of collected water. There were several design constraints for the prototype derived from its intended use on Mars. The robot had to: be remotely operated; weigh less than 60kg; operate on a limited power supply of 10A at 120V; apply no downward force greater than 150N; remove between 0.3-0.6 m of regolith; and operate in temperatures as low as -26°C. The Northeastern University Planetary Articulating Water Extraction System (*NU-PAWES*) team won the 1st Place Award by collecting 3.3 L over 12 hours in the challenge. This record amplified the harvested water amounts from milliliters in 2017 to multiple liters in 2018 by demonstrating novel technologies at TRL 4. *NU-PAWES* operates in four stages, (i) a 1-hour cycle of using an auger to create a 2in diameter hole through regolith to expose ice, (ii) a melting process using a multi-axis, 360° articulating heater, (iii) the extraction of water by a reversible pump system, and (iv) an electroflocculation filtration process. In our laboratory and field validation at NASA Langley Research Center, *NU-PAWES* demonstrated versatility to drill holes through overburden of varying consistencies and temperatures. The system effectively minimized the energy spent on overburden removal and maximized accessibility to ice reserves.

2. Goals and Expected Significance

Motivated by our team's expertise in engineering novel robot designs, we claim novelty in three technical areas to achieve the overall project goal of realizing a robotic ice penetration and navigation system for Europa, *TRIDENT* (Figure 3):

1. Development of a novel, modular and potentially reconfigurable system with a hybrid melting and drilling module to optimize power consumption,
2. Development of perception-based path planning and control algorithms for TRIDENT in pursuit of targets for risk minimization,
3. Development of a suite of datasets and test methods to quantify key capabilities of *TRIDENT* for amplifying project's significance to enable benchmarking and future development efforts in the field.

Aligned with these, this project has the following four interlinked research and development goals that will be executed collaboratively by the research team.

(1) Goal 1: Designing *TRIDENT*: We will execute a model-based design methodology to realize subsystems both scaled and actual size to develop *TRIDENT* to meet the set of complete engineering design specifications to be developed early in the project timeline. Key features of the design will include a hybrid ice melting/drilling and locomotion modules for persistent and efficient progress in varying ice characteristics; a perception module for proprioception to achieve self-aware operations and exteroception for subsurface navigation; as well as a tetherless communications link through strategically deployed transducers. This effort, to the best of our knowledge, will be a first attempt towards developing a system level implementation of a subsurface exploration technology capable of altering its path either to minimize risks or to pursue targets of interest during the course of a mission.

(2) Goal 2: Controlling *TRIDENT*: In order to address unknown and dynamic conditions during a potential Europa mission to its subsurface ocean, we will develop a hierarchical control architecture. At the lowest level, control paradigms that shifts the operations from drilling to melting for power optimization, velocity control for drilling under varying environmental conditions, and controllers for transducer deployment will be implemented. At the highest level, perception based algorithms will be developed to steer the course of *TRIDENT* using data from the GPR, monocular low-resolution cameras, and tactile sensors. Inspired by research enabling underwater autonomous vehicles to navigate using side-scan/forward-looking sonar, cameras, inertial measurement units (IMU), and

Doppler velocity logs (DVL), we will develop similar navigation and localization algorithms appropriate for the mission that rely on GPR, cameras, IMUs, and odometry. Our main objective will be to develop algorithms that can fuse the GPR information along with the traditional navigation. Because this is a significant difference from most robotic systems navigating on Earth, we will also be forced to develop new decision making protocols and path planning techniques that are tailored to the strengths and weaknesses of a GPR-vision based system. Our secondary objective is to utilize these sensors to determine the quality of ice directly below TRIDENT and alter the drilling behavior to match.

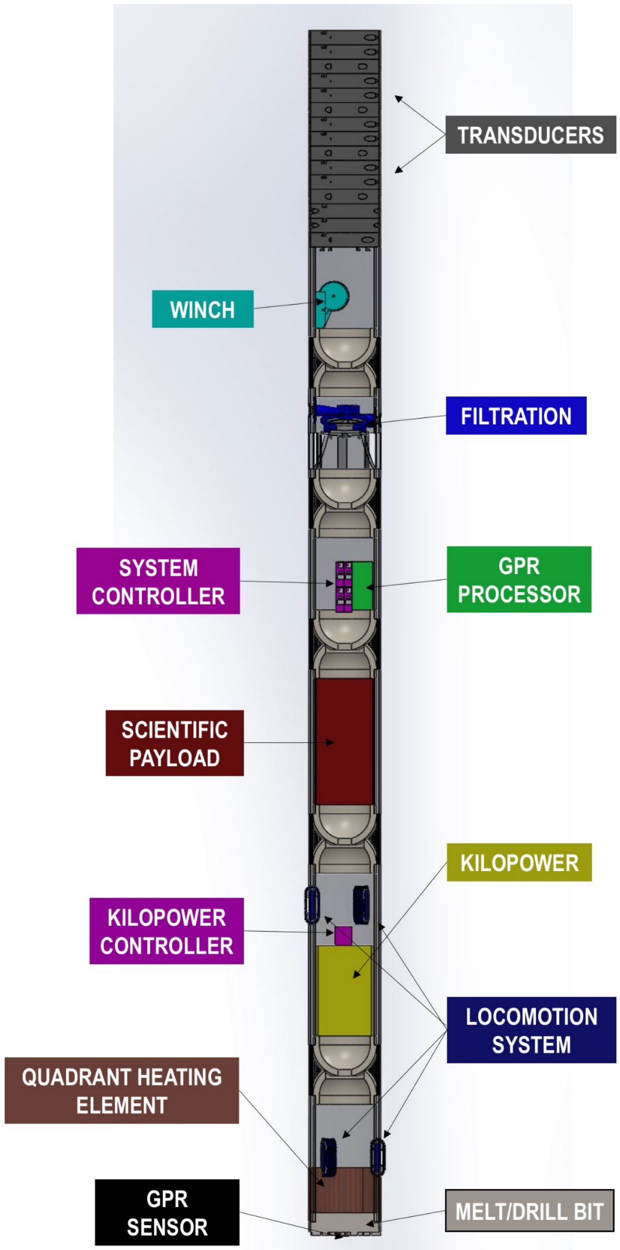

Figure 3: TRIDENT conceptual design and proposed system modules.

(3) Goal 3: Validating *TRIDENT:* We will design experiments, perform analytical evaluation and experimental validation of *TRIDENT* both in simulation and on actual hardware. This will be done for each subsystem in a laboratory setting, for the entire system in a scaled down prototype and potentially for the entire system in the field.

(4) Goal 4: Accelerating SESAME Research: We posit that ground penetrating radar (GPR) technology holds great promise in SESAME research. However, this will need to be validated through analytical and experimental methods. We propose to create a GPR dataset for varying ice conditions. This dataset will enable future pattern recognition, and machine learning research directions to characterize the ice block that *TRIDENT* is penetrating. In addition, we will design replicable experiments to enable benchmarking within the SESAME community.

Rather than being an afterthought, we will organize technology demonstrations and field tests with participation of the stakeholders, thinking aloud sessions and testing and evaluation of the engineered robotics assets in human-robot teams. In order to realize this, we will develop intuitive and adaptable user interfaces in order to easily assign tasks for human and robot team members in mission scenarios. We will develop a holistic software architecture that will enable team leaders to easily and intuitively factor tasks to maximize the utility in the human-robot teams and generate high-level robot tasks which will be performed using the supervisory control framework.

3. Impact of the Proposed Work

The proposed research will have impacts both in the context of space missions of interest to NASA and also other related fields facing similar challenges, such as mining, search and rescue, and surveying at the poles. We will leverage standardized hardware and software components implemented in a modular manner for making our designs easily transferable and applicable to a wide variety of fields and applications. The engineering research will enable efficient methods subsurface exploration using robotic systems. The proposed research will impact the following areas outlined by NASA in the SESAME solicitation:

- Ice penetration system capable of penetrating an ice sheet on an icy world.
- Optimized total system mass (<200 kg).
- System reliability to mitigate the inability to make forward progress.
- Ice penetration system capable of efficiently progressing through realistic ice profiles expected on Europa.

Furthermore, the project impact can be found at:

- Novel navigation algorithms using GPR sensor data.
- Technologies and best practices for developing Earth analog ice sampling systems and testbeds.

4. Relevance of the Proposed Work

Per solicitation, SESAME is relevant to the planetary science questions and goals in the NASA *Science Plan*. The holistic approach being proposed by the investigators team to design a steerable, tetherless ice penetration system is potentially high-risk, yet it will be high-impact in creation and validation of new technologies in order to meet the SESAME program objectives.

5. Technical Approach and Methodology

This project will leverage our collective experience from the DARPA Robotics Challenge (DRC), NASA Sample Return Robot and Space Robotics Challenges (SRC) in humanoid robot control, constrained and dexterous manipulation, perception, and operator interfaces to develop a systematic model-based task validation methodology. Furthermore, our team has expertise in understanding material properties of ice forms. We will leverage our team's prior robot design experience ranging from biomimetic quadrupedals, to exploration rovers with articulated arms to develop the system (Dimitrov 2013, Amato 2012, Chernyak 2012). The SESAME program poses an engineering design problem with critical constraints the need to be met. We identify design requirements in the following categories: interface requirements, physical design requirements (SWAP), control/sensor requirements, operational requirements. The interface requirements include: *TRIDENT* will have a reliable and capable ice penetration mechanism; the system will support universal interfaces for power and communications between modules. The physical design requirements for the system are as follows: the system will meet the weight and power requirements posed by the SESAME program; the system will have a universal interface to allow for modularity and reconfigurability in order to meet varying requirements to achieve a robust system. The control and sensing requirements are as follows: system will include force and position feedback at each joint and critical locations; system will include visual sensors for self-inspection, and navigation. Operational requirements include: *TRIDENT* will avoid potential hazards; the system will have capability to alter its descent course. It should be noted that this is not a complete list of design requirements. We provide this list to demonstrate our understanding of the design process. A complete and correct set of requirements will be developed by employing a model-based design process and iterative systems engineering methodology in collaboration with the project stakeholders.

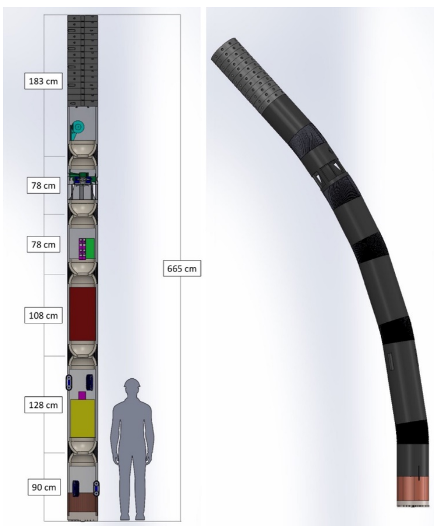

Figure 4: *TRIDENT* will have a cylindrical design with approximate length of 6.6 m and diameter of 0.4 m (left). The design achieves a 15 m turning radius (right).

5.1. Designing *TRIDENT*

Within the scope of this project, we will explore the design space for a tetherless, autonomous robotic system (*TRIDENT*) equipped with a heated rotary drill to penetrate and navigate through the Europan ice, collect scientific samples, and return data to the surface at the landing site (**Figure 3**). We propose to develop and validate three critical subsystems of *TRIDENT*, first individually, and then as an integrated system. These subsystems are (1) an ice-displacement system that can penetrate different solid substrates and reform ice behind it; (2) a locomotion system that can drive and steer in solids, liquids, and subsurface voids; and (3) a navigation system that can detect and maneuver around different subsurface regions.

TRIDENT will have a modular design and can be implemented using a "train cars" approach. Each of the aforementioned subsystems will be housed in one or more distinct modules. This modular and potentially reconfigurable design of the robotic system will allow *TRIDENT* to turn at radii as small as 15 meters in its full implementation (**Figure 4**). This modular design approach will enable the navigation and locomotion systems to strategically alter *TRIDENT*'s path to avoid potential hazards, and seek targets of interest in its course to Europa's ocean.

The modules, starting at the front of the robot (*TRIDENT*'s head), will contain the following systems (**Figure 3**): (1) a drilling system capable of penetrating ice and a locomotion system to move *TRIDENT* forward; (2) a power system that will provide power to the vehicle as well as waste heat to assist the drilling system by melting the ice; (3) the scientific payload with instruments that can collect a variety of data and samples; (4) a computing system and array of sensors that will handle both TRIDENT's navigation and communications with the surface; (5) a filtration system that can sort out "dirty" and "clean" components of the melted ice, and refreeze those components systematically; (6) a tether that will allow *TRIDENT* to descend safely through less firm, slush-like conditions or potential hollow regions; and (7) a set of droppable transceivers that will assist with communications through the ice back up to Europa's surface. Each module will connect to its neighbors using a standardized ball and socket joint, with a hollow center which will mechanically allow data and power connection to run between modules. These

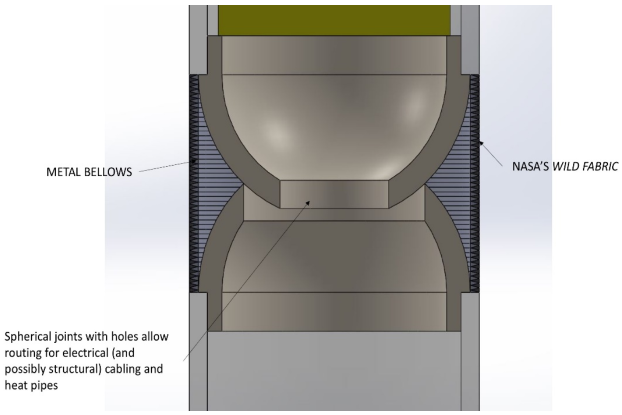

Figure 5 : A standard mechanical and electrical interface will be designed to enable a modular and reconfigurable design for *TRIDENT.*

connections will be sealed on the outside using metal bellows, which can bend freely as the modules actuate in relation to each other (**Figure 5**) making sure no particles become lodged within the system. The joint design will first be developed and optimized using finite element analysis to ensure that it can support the system weight and drilling forces at maximum angular displacement. We expect that the first joint (connecting Modules 1 and 2) will be the critical feature due to the large forces it must transmit between the drill head/locomotion system on one side, and the power system (which comprises the majority of the system weight) on the other. To mitigate the risk this joint poses to our success, we will consider fusing Modules 1 and 2, or moving the locomotion system above the power system to help support its weight. Each module is described in more detail, next.

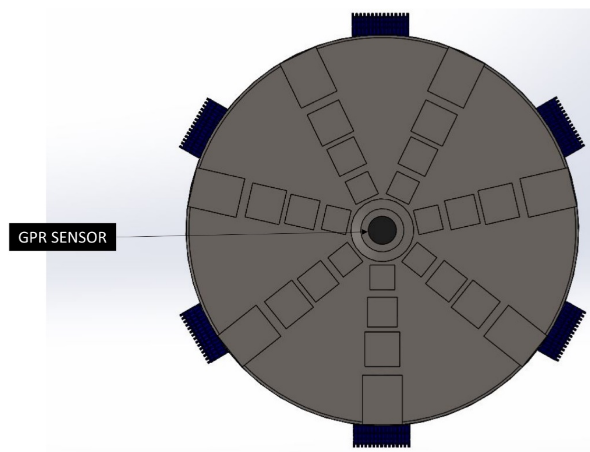

Figure 6 Drill head design concept, bottom view.

Module 1: Drilling and Locomotion: The leading module of *TRIDENT* will contain both a drilling system and a locomotion system that will allow it to penetrate through the expected ice conditions on Europa. The drill head will consist of a heated, flat, rotary head with a set of small teeth protruding from the surface of the head, inspired by the faces of tunnel boring machines. While drilled material passes through the head of typical tunnel boring machines, *TRIDENT*'s drilling head will cut small ice chips from the borehole surface, allowing the ice to melt more quickly. As *TRIDENT* descends, the melted water will pass along the sides of the vehicle to the filtering module at the rear. If *TRIDENT* were to encounter a solid sediment layer or larger sediment particles which it could not navigate around, it might struggle with the above design. This risk will be mitigated by designing the head to be slightly conical. This would allow solid, unmeltable materials to be pushed to the sides of the borehole as the vehicle progresses (**Figure 6**).

The locomotion system contained in the head module(s) of *TRIDENT* will serve three purposes. The first is to provide pressure on the drilling face. While the weight of the robot will provide a force on the bit, additional force control can both result in faster drilling/melting process and avoid factors that may cause the stalling of the drill. The second purpose of the locomotion system is to provide a counter-torque to keep the robot from spinning as the drill head spins. The third role of the locomotion system is to steer the robot in three-dimensional space. We will compare two designs: one using wheels and one using treads. Each design will first be optimized using finite element analysis to determine holding forces and stress concentrations, and then prototypes of each will be built and tested under realistic conditions by placing them in a cylindrical ice hole and measuring their maximum load/force, power consumption, and resilience against off-axis forces. The system itself will consist of three spring-loaded wheels/tracks with sharp teeth protruding from the vehicle. These teeth will be capable of penetrating and anchoring to the walls of the borehole. They will be oriented at 120° to each other, and can be actuated independently. This will allow the vehicle to turn in any direction by controlling the wheels at different speeds (even in reverse), acting as a differential drive system. The leading module will be the only one with this translational and directional control; the following modules will freely turn about the joints and trail along the path it takes (**Figure 7**).

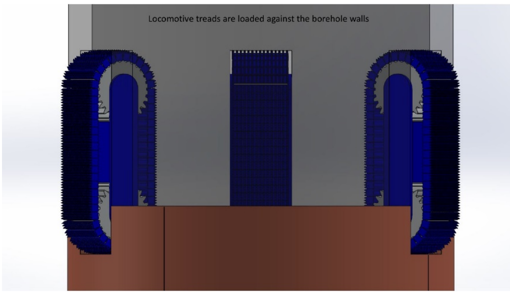

Figure 7: Wheel/tread locomotion system design concept.

Module 2: Power System: *TRIDENT* will be designed to incorporate the Kilopower Fission Power System (KFPS) as its sole power source, using both the electrical power and thermal waste to operate. In addition to the KFPS, this module will contain a power path controller to manage energy distribution throughout *TRIDENT*. It is estimated that the electronics on board will operate on around 60 W of electric power. The FPS generates a large amount of waste heat, which will be collected to Module 1 via heat pipes through the joint between Modules 1 and 2. This waste heat will be used to heat the drilling head in Module 1. One risk is that the joint between Modules 1 and 2 is not capable of transporting the necessary thermal power – if we find this to be true, we will ‘fuse’ Modules 1 and 2 into a single module.

Module 3: Scientific Payload: The scientific payload will be primarily constrained to the third module. It will house scientific devices to probe the environment surrounding the robot during its descent through the ice. It is included in the design to demonstrate the modularity of *TRIDENT*.

Module 4: Computing, Navigation, Communications: The fourth module of *TRIDENT* will house the vehicle’s central controller, navigation system, communications system, and other electronics. The navigation system will use Ground Penetrating Radar with a primary 200 MHz antenna and a secondary 100 MHz antenna to detect things such as obstacles, voids, and dense patches of ice up to 60 meters ahead of the drill. The robot’s central controller will then analyze this information and calculate an optimized route to reach the subsurface ocean. The central computation unit will also fuse signals from *TRIDENT*’s various sensors and direct it to a main receiving module on the surface via the communications link. Based on the ice conditions predicted on Europa, *TRIDENT* will be capable of transmitting 10 KHz, although the relationship between transmission rate and distance is nonlinear. One interesting consideration is that signals can travel further in colder ice. As *TRIDENT* progresses, the distance between transceivers must be reduced since the further down, the ice becomes warmer, and it is essential to space the transceivers to maintain a 10 kb/s data rate. These transceivers will be dropped in the meltwater behind the drill and will refreeze with the ice. They will boost the signal along on its way to the surface receiving unit allowing for faster transmission of data with less noise. These transceivers are discussed further in Module 7.

Module 5: Filtration: *TRIDENT*'s fifth module will contain a filtration system to purify and refreeze ice behind the vehicle. Europa's ice is thought to be dirty, and these impurities increase the attenuation of radio signals through ice, hindering communication. This module will aim to filter out these dirty parts of the ice, creating an "information highway" of relatively pure ice. Melt water from the tip will travel up the sides of the vehicle to this module, and then enter *TRIDENT* at the base of this module. The water will then enter a centrifugal filter which will push all the solid dirty components of the ice outward to the sides of the borehole, creating a cleaner core of water in the center. The cleaner water will then exit at the top of this module and continue along behind the vehicle where it will finally freeze, providing improved radio transmission to both the transceivers and the surface.

Module 6: Winch and Tether System: The sixth module will contain a tethered rappelling system. It is believed that there exists approximately 1 km of thick slush separating Europa's ice crust and fully liquid ocean, and intermittent voids throughout the ice. In these environments, *TRIDENT* would begin to fall and may become unrecoverable. To prevent this, once *TRIDENT* detects a slush or void ahead, the tether will lock itself into the last portion of solid ice using a controllable attachment. The vehicle will then lower itself from this point using cable stored in a spool in this module.

We will pay particular attention to design of the tether recovery for repeated rappelling operations. One risk is that the anchor will fall through the void faster than the system can recover the tendon. To mitigate this risk, we plan to bias the winch with a constant-torque spring. This will have the complementary effects of reducing the motor torque necessary for controlled lowering and increase the recovery speed to match the free-fall speed of the anchor.

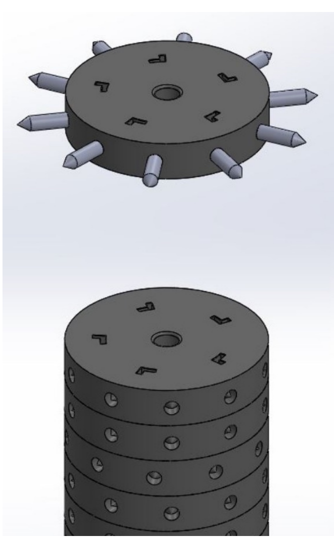

Figure 8: Concept design for *TRIDENT*'s transceivers.

Module 7: Transceivers: The final module of *TRIDENT* will contain a set of 15 radio transceivers, as described as part of Module 4. Each of these transceivers will be puck-like in shape (30 cm diameter by 3 cm thick) and contain a lightweight radioisotope heater unit**.** The transceiver housing will also have sensors for remote biosignature detection. For data transfer, each transceiver will contain a transmitter and receiver, integrated and external memory, and a microcontroller. For the transmitter and receiver to run in the same duty cycle, the power requirements are higher, however the transceivers will act on a watchdog system and will wake up when triggered by the modules on either side of the sequence. To protect against data loss, each transceiver will receive data wirelessly and immediately store it in its EEPROM before sending it to the next transceiver in line. After this, the microcontroller will write the data to the hard drive before going back to sleep. This protects the data in the case of a power interruption or inability to connect to the next transceiver. Additionally, the microcontrollers will automatically poll for the next transceiver in the sequence and in the case of no response, transmit data to the next one in the link to protect against transmission gaps. The pucks will also contain amplifiers that can be engaged to boost *TRIDENT*'s radio signal as it travels to the main surface unit. This module will control the release of these transceivers in intervals, adjusted by the central computer depending on the ice conditions. Assuming an ice crust thickness of 30 kilometers, we expect 13 transceivers are needed. 2 additional ones are included in the design for redundancy to attain a transmission quality of at least 10 kb/s.

5.2. Controlling *TRIDENT*

The proposed research in essence requires the seamless balancing of control between resource management and task completion, which is primarily progressing through the ice sheet. The goal will be to accomplish control architecture for *TRIDENT* for operations in complex and harsh subsurface ice environment. This research task will focus on design and implementation of on-board computation and control for *TRIDENT*.

Control Software Modules. We will build upon our work reported in (Carlone 2013, Amato 2012, Akmanalp 2012, Banerjee 2014, Atkeson 2014) and continue to design and develop autonomy software modules for robot navigation. We will design and realize navigation, mapping, localization, perception and low-level control software modules. Lessons learned from these preliminary work will be translated to computation block for *TRIDENT*. We will implement color, texture, feature based pattern and object recognition, visual odometry, motion-primitives based navigation, and SLAM algorithms. Slow, power-efficient computational can be achieved due to slow motions of the robot. The uncertainties in systems state will be addressed by generating actions for a range of situations and using probabilistic decision making techniques such as partially observable Markov decision processes. We will also take into account the data from sensors to minimize the effect of system uncertainties on the proper operation of the system.

Hierarchical Navigation Framework. We will design and implement a navigation architecture for developing autonomous behaviors for *TRIDENT* by creating multiple levels of planners from controlling individual components of the robot to planning the high level paths to provide flexibility and reliability in operations. Moreover, we will extend our constrained motion control framework (Long 2014) to the new platform proposed here. At the highest level there will be a single nondeterministic finite state machine that will monitor and control the process flow. Separate planners will be designed to run for drilling, heating, and locomotion controllers that allow the high level planner to command actions to subsystems. The drive system will have two levels of planning, a higher level planner that generates waypoints that the robot will use to get to a final goal and a lower level drive planner that generates a velocity for the robot to get to each waypoint. The low-level path planner will obey the power requirements posed by the overall system. Multiple motion-primitives based will be generated and the resultant trajectories will then be scored based on a number of factors including power requirements, time to execute, and a risk factor. The best control inputs will then be communicated to the higher level planner for evaluation and execution. This process will be executed continuously. In case of failures due to environmental conditions such as stalled drill, local planner will support a number of recovery behaviors including backing away and reorienting the head. Moreover, we will also develop a number of motion templates to provide the system with autonomy for safe operation and recovery in failure modes.

Material-Based Drilling Optimization. We expect that different ice types (ductile/brittle, pure/polluted) will have different optimal drilling approaches, in terms of speed, temperature, and head pressure. As we characterize the drill performance on different types of ice, we will note how the ice quality relates to optimal drilling approach, and develop algorithms to relate sensor readings to ice quality, using our cameras to quantify the sediment density and temperature to determine the ice's mechanical properties. In this way, we can deduce an optimal drilling strategy that dynamically adjusts based on sensor readings, resulting in a more efficient system across a large range of conditions.

5.3. Validating *TRIDENT*

The research and development plan outlined in this proposal is aimed at taking a bold step to realize an ice penetrating robotic system for exploration of ocean worlds. The project timeline will enable the research team to realize a model-based design methodology for implementing a new robot platform (*TRIDENT)*. Each year, time is dedicated to the perform rigorous evaluations to maximize the impact and broad implementation of the research outcomes developed in the scope of the project.

We envision that a holistic approach will enable our team to accomplish our research objectives. We will overcome the design challenges by applying a system design process comprising three phases: (1) decomposition and definition, (2) implementation, and (3) integration and recomposition. We will monitor our progress utilizing project management tools similar to other projects we work on including the DARPA Robotics Challenge and NASA Space Robotics Challenge. Our validation strategy builds on our experience developing robot designs, test scenarios, our DRC experience, and our experience with developing autonomous robot skills and can be described by a set of key features:

(1) We will evaluate each subsystem to identify and implement methods to realize based on specifications. By testing and failing early, we will be able to improve the functionality, reliability and efficiency.
(2) From the beginning of the project timeline, we will design experiments and validate design under realistic circumstances.
(3) In software development, we propose to use an iterative model-based design approach to specify and verify requirements for each subsystem, develop models for system, and subsystem functionality as well as the environment, select and compose models of computation, simulate the systems individually and as a whole, and verify and validate the algorithm designs on the physical robot. We will design and implement event-driven finite state machines (FSM) for concept of operations.

5.4. Accelerating SESAME Research

In order to amplify impact, we will develop benchmarks in terms of data collection, analysis and experimentations. Within the scope of each project, we will develop experimental procedures, collect and analyze data to draw conclusions. The project team will follow good practices in experimental design and procedures by: (1) Clearly describing the underlying assumptions, (2) Explicitly presenting the evaluation criteria, i.e. the criteria for success, (3) Clearly recording the measurable performance criteria, (4) Explicitly describing and justifying the measurement methods and procedures, (5) Providing ample and sufficient details on methods and parameters needed to reproduce the experiment, (6) Carefully executing the experiments and identifying the factors effecting the performance, (7) Providing precise and valid conclusions.

Proposed data sets include:

- GPR dataset over ice blocks with different characteristics
- Drilling dataset operating inside ice blocks with varying characteristics
- Melting dataset operating inside ice blocks with varying characteristics

In order to collect these dataset, we will use CU's facilities. Based on the best candidates determined from laboratory and spectroscopy studies of Europa's surface, which are informed by chondritic abundances, we will create ice samples of various salt/acid compositions. These will include mixtures of ice with hydrated species of magnesium sulfate, sodium sulfate, sodium chloride and sulfuric acid. Following protocols for creating "standard ice" samples, we will control composition, grain size, and porosity of ice samples in order to constrain the GPR signal. Furthermore, we will test the drilling system's efficiency by preparing large volume ice samples containing a variety of soluble and insoluble phases, including various salts and acids, as well as particles of alumina, silica, and graphite. All of these second phases are known to affect the strength of the ice (e.g. McCarthy, 2011; Moore, 2014) and in the case of the soluble phases influence the melting temperature.

Based on these datasets, we will also develop a simulation environment using DARPA and NASA funded physics-based GAZEBO environment to enable other researcher to test their own approaches to ice penetration systems.

5.5. Estimated Power and Mass Budget

We performed a preliminary analysis for power and mass budgets for *TRIDENT.* The conclusions are presented in Tables 1 and 2. It is verifiable that the design will be realized within the requirement.

Table 1 Power system budget for *TRIDENT* under three different operating states.

State 1: Cryogenic Ice (5km)							
Subsystem	**Power Req.**	**Time Used (hours per day)**	**Percent Time On**	**Power Used**		**Total Power (W)**	**Percent of Power Used**
Drill	300	24	100.00%	300.00		420	97.64%
Locomotion	600	2	8.33%	50.00			
Communication	1.3	1.11	4.63%	0.06			
Computation	60	24	100.00%	60.00			
Sensors (GPR's)	0.8	1	4.17%	0.03			
				410.09			
State 2: Warm Ice (10km)							
Subsystem	**Power Req.**	**Time Used (per day)**	**Percent Time On**	**Power Used**		**Total Power (W)**	**Percent of Power Used**
Drill	300	12	50.00%	150.00		420	85.74%
Locomotion	600	6	25.00%	150.00			

Communication	1.3	1.11	4.63%	0.06			
Computation	60	24	100.00%	60.00			
Sensors (GPR's)	0.8	1	4.17%	0.03			
				360.09			
State 3: Slush (5km)							
Subsystem	**Power Req.**	**Time Used (per day)**	**Percent Time On**	**Power Used**		**Total Power (W)**	**Percent of Power Used**
Drill	300	0	0.00%	0.00		420	26.21%
Locomotion	600	2	8.33%	50.00			
Communication	1.3	1.11	4.63%	0.06			
Computation	60	24	100.00%	60.00			
Sensors (GPR's)	0.8	1	4.17%	0.03			
				110.09			

Table 2: Estimated Mass Budget for *TRIDENT*

Subsystem	Mass
Power Source (Kilopower)	413 kg
Frame	20 kg
Articulated Drill	20 kg
Wheels/Treads	30 kg
Motors	30 kg
Tether	50 kg
Electronics	15 kg
Filtration System	15 kg
TOTAL	**593 kg**

6. Implementation Plan

It is expected that this project will result in robotics technologies (including hardware, software, interfaces and systems level) that will reach TRL 4. We will develop a full scale prototype of the *TRIDENT* system and demonstrate testing in the laboratory settings. This project involves an interdisciplinary team of researchers who will coordinate their efforts toachieve the multifaceted goals described above. Padir is responsible for the overall project and will lead the effort based on his expertise in robot control and experience with running large scale projects such as the DARPA Robotics Challenge and Hosting NASA's R5. Major decisions will be taken by consensus among the principal investigators with input from NASA engineers as needed. The entire project team will hold weekly meetings to which all investigators and researchers involved will be expected to join, either in person or via videoconferencing. At these meetings, general progress will be discussed within each component and plans for the next cycle will be established depending on the circumstances. Smaller subgroups will hold more frequent meetings.

6.1. Schedule

In order to achieve TRL 4, we will employ a spiral development process to assure tight coordination across the team in achieving its milestones. Rather than separate sub-teams working all in parallel, doing subsystem development and testing, but postponing integration until late in the project, we will structure the project as a series of fully integrated prototypes starting with basic systems and with each cycle we add more functionality. In other words, at any time in the project timeline, we will have functional prototypes of the proposed system to demonstrate capabilities of increasing complexity.

Year 1 (3 cycles):

- **Design:** Design requirements development. Agile hardware prototype development. Low-level controller design.
- **Control:** Agile software development and framework design. Hardware validation, modeling and system identification
- **Validation:** Subsystem validation of designs, control and communications.
- **Acceleration:** Domain knowledge and establish requirements definition and use cases. Data event logging system implemented. Testing and results evaluation for each spiral.

Year 2 (3 cycles):

- **Design:** Revisions as required based on learnings from prior spirals. Enhanced control performance. Deployment and retrieval systems complete.
- **Control:** Revisions as required based on learnings from prior spirals. Computation optimization to enable deployment. High-level decision-making for improved robot autonomy.
- **Validation:** Integrated system validation of designs, control and communications. Analysis of validation results.
- **Acceleration:** Dataset for perception, control, characterization, and energy use. Packaging of software and hardware designs for sharing.

6.2. Challenges and Mitigation Plan

Despite the project team's extensive expertise in managing large scale projects with aggressive timelines, we anticipate challenges associated with hardware compatibility, integration, interoperability, equipment and hardware component acquisition in addition to research and development challenges resulting from the interdisciplinary nature of the proposed development effort. We will overcome challenges using frequent communication among team members in each development cycle. We will try to identify problems earlier, with the benefit of rapid cross team corrections to modify the technical approach. In this age of information and connectivity, we are confident that we will successfully achieve the proposed partnerships and research and training activities.

7. Conclusion

In conclusion, this *TRIDENT* team of investigators with complementary expertise proposes the development of a modular and reconfigurable ice penetration system with unique features to advance technologies beyond the state of the art. We will amplify the expertise of the PI team by mobilizing highly-motivated student researchers to meet the ambitious, yet high-impact, goals of the proposed system, *TRIDENT.*

References

Carlson, R.W., Anderson, M.S. , Johnson, R. E., Schulman, M.B. and Yavrouian, A. H. (2002) Sulfuric acid production on Europa: the radiolysis of sulfur in water ice. Icarus, 157, 456-463.

Chyba, C. F. (2000) Energy for microbial life on Europa. Nature 403, 381-382.

Collins, G. C., McKinnon, W.B., Moore, J.M., Nimmo, F., Pappalardo, R.T., Prockter, L.M., and Schenk, P.M. (2009) Tectonics of the outer planet satellites. Planetary Tectonics, 11.

Dalton, J.B., Prieto-Ballesteros, O., Kargel, J.S., Jamieson, C.S., Jolivet, J. and Quinn, R. (2005) Spectral comparison of heavily hydrated salts with disrupted terrains on Europa. Icarus, 177, 472-490.

Fischer, P.D., Brown, M. E. and Hand, K. P. (2015) Spatially resolved spectroscopy of Europa: the distinct spectrum of large-scale chaos.

Hand, K. P., Chyba, C. F., Priscu, J. C. Carlson, R. W., Nealson, K. H. (2009) in Europa, ed. R. T. Pappalardo et al. (Tucson, AZ; Univ. Arizona Press), 283.

Helfenstein, P. and E. M. Parmentier (1983) Patterns of fracture and tidal stresses on Europa. Icarus 53, 415-430.

Hoppa, G. V., Tufts, B. R., Greenberg, R., and Geissler, P.E. (1999) Formation of Cycloidal Features on Europa, Science, 285, 1899-1902.

Kattenhorn, S. A., Prockter, L. M. (2014) Evidence for subduction in the ice shell of Europa, Nature Geoscience 7, 762-767.

Marshall, S. T., Kattenhorn, S. A. (2005) A revised model for cycloid growth mechanics on Europa: Evidence from surface morphologies and geometries. Icarus 177, 341-366.

McCarthy, C., H. M. Savage, T. Koczynski, and M. A. Nielson (2016) An apparatus to measure frictional, anelastic, and viscous behavior in ice at temperate and planetary conditions, *Rev. Sci. Inst. 87, 055112, doi: 10.1063/1.4950782*

McCarthy, C., R.F. Cooper, D.L. Goldsby, W.B. Durham, and S.H. Kirby (2011) Transient and Steady-state Creep Response of Ice-I and Magnesium Sulfate Hydrate Eutectic Aggregates, *Journal of Geophys. Res. – Planets*, doi:10.1029/2010JE003689

McCarthy, C., R.F. Cooper, S.H. Kirby, K.D. Rieck, and L.A. Stern (2007) Solidification and microstructures of binary ice I/hydrate eutectic aggregates. *American Mineralogist*, Vol. 92, 1550-1560

McCord, T.B., Hansen, G.B., Fanale, F.P., Carlson, R.W. matson, D.L., Jounson, T.V., Smythe, W.D. Crowley, J.K., Martin, P.D., Ocamp, A., Hibbitts, C.A. Granahan, J.C., and the NIMS Team (1998) Salts on Europa's surface detected by Galileo's near infrared mapping spectrometer. Science, 280, 1242-1244.

Nimmo, F. (2004) Dynamics of rifting and modes of extension on icy satellites, J. Geophys. Res. 109, E01003.

Amato, J. L., Anderson, J. J., Carlone, T. J., Fagan, M. E., Stafford, K. A., & Padir, T. (2012, October). Design and experimental validation of a mobile robot platform for analog planetary exploration. In *IECON 2012-38th Annual Conference on IEEE Industrial Electronics Society* (pp. 2686-2692). IEEE.

Banerjee, N., Long, X., Du, R., Polido, F., Feng, S., Atkeson, C. G., ... & Padir, T. (2015, November). Human-supervised control of the ATLAS humanoid robot for traversing doors. In *Humanoid Robots (Humanoids), 2015 IEEE-RAS 15th International Conference on* (pp. 722-729). IEEE.

Chernyak, V., Flynn, T., O'Rourke, J., Morgan, J., Zalutsky, A., Chernova, S., ... & Padir, T. (2012, July). The design and realization of a high mobility biomimetic quadrupedal robot. In *Mechatronics and Embedded Systems and Applications (MESA), 2012 IEEE/ASME International Conference on* (pp. 93-98). IEEE.

DeDonato, M., Dimitrov, V., Du, R., Giovacchini, R., Knoedler, K., Long, X., ... & Moriguchi, H. (2015). Human-in-the-loop Control of a Humanoid Robot for Disaster Response: A Report from the DARPA Robotics Challenge Trials. *Journal of Field Robotics*, *32*(2), 275-292.

DeDonato, M., Polido, F., Knoedler, K., Babu, B. P., Banerjee, N., Bove, C. P., ... & He, P. (2017). Team WPI-CMU: Achieving Reliable Humanoid Behavior in the DARPA Robotics Challenge. *Journal of Field Robotics*, *34*(2), 381-399.

Dimitrov, V., DeDonato, M., Panzica, A., Zutshi, S., Wills, M., & Padir, T. (2013, October). Hierarchical navigation architecture and robotic arm controller for a sample return rover. In Systems, Man, and Cybernetics (SMC), 2013 IEEE International Conference on (pp. 4476-4481). IEEE.

Dimitrov, V., & Padır, T. (2014, August). A shared control architecture for human-in-the-loop robotics applications. In *Robot and Human Interactive Communication, 2014 RO-MAN: The 23rd IEEE International Symposium on* (pp. 1089-1094). IEEE

Long, X., Wonsick, M., Dimitrov, V., & Padır, T. (2016, November). Task-oriented planning algorithm for humanoid robots based on a foot repositionable inverse kinematics engine. In *Humanoid Robots (Humanoids), 2016 IEEE-RAS 16th International Conference on* (pp. 1114-1120). IEEE.

M.A. Akmanalp, R.M. Doherty, J. Gorges, P. Kalauskas, E. Peterson, F. Polido, S.S. Nestinger, and T. Padir. Design and Realization of an Intelligent Ground Vehicle with Modular Payloads. In IS&T/SPIE Electronic Imaging, Intelligent Robots and Computer Vision XXIX: Algorithms and Techniques Conference, Burlingame, CA, January 2012.

M.A. Akmanalp, R.M. Doherty, J.J. Gorges, P.S Kalauskas, E.E. Peterson, F. Polido, and T. Padir. Realization of Performance Advancements for WPI's UGV - Prometheus. Technical report, Worcester Polytechnic Institute, 2010. http://www.wpi.edu/Pubs/E-project/Available/E-project-042711-130820/ .

J.L. Amato, J.J. Anderson, T.J. Carlone, M.E. Fagan, K.A. Stafford, and T. Padir. ORYX 2.0: A Planetary Exploration Mobility Platform. Technical report,Worcester Polytechnic Institute, 2012. http://www.wpi.edu/Pubs/E-project/Available/E-project-042612-131146/.

J.L. Amato, J.J. Anderson, T.J. Carlone, M.E. Fagan, K.A. Stafford, and Padir T. Design and experimental validation of a mobile robot platform for analog planetary exploration. Proc. IECON 2012: 38th Annual Conf. of the IEEE Industrial Electronics Society, Montreal, CA, Oct. 25-28, 2012.

Atkeson, C. G., Babu, B. P.W. , Banerjee, N., Berenson, D., Bove, C. P., Cui, X., DeDonato, M., Du, R., Feng, S., Franklin, P., Gennert, M. A., Graff, J. P., He, P., Jaeger, A., Kim, J., Knoedler, K., Li, L., Liu, C., Long, X., Padir, T., Polido, F., Xinjilefu, X. Team WPI-CMU: Achieving reliable humanoid behavior in the Darpa Robotics Challenge. J. Field Robotics.

N. Banerjee, Xianchao Long, Ruixiang Du, F. Polido, Siyuan Feng, C. G. Atkeson, M. Gennert, and T. Padir. Human-supervised control of the atlas humanoid robot for traversing doors. In Humanoid Robots (Humanoids), 2015 IEEE-RAS 15th International Conference on, pages 722–729, Nov 2015.

T. Carlone, J. Anderson, J. Amato, V. Dimitrov, and T. Padir. Kinematic control of planetary exploration rover over rough terrain. Systems, Man, and Cybernetics (SMC), 2013 IEEE International Conference on, 2013.

T.J. Carlone, J.J. Anderson, J.L. Amato, V.D. Dimitrov, and T. Padir. Kinematic control of a planetary exploration rover over rough terrain. In Systems, Man, and Cybernetics (SMC), 2013 IEEE International Conference on, pages 4488–4493, Oct 2013.

Moore, P.L. (2014) Deformation of debris-ice mixtures, Reviews of Geophysics, 52(3), 435-467.

McCarthy, C., R.F. Cooper, D.L. Goldsby, W.B. Durham, and S.H. Kirby (2011) Transient and Steady-state Creep Response of Ice-I and Magnesium Sulfate Hydrate Eutectic Aggregates, Journal of Geophys. Res. – Planets, doi:10.1029/2010JE003689