Northeastern University

PARSEC: **P**ercussive **A**nd **R**otary **S**urveying & **E**xtracting **C**arousel

NASA RASC-AL Moon to Mars Ice & Prospecting Challenge





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Nomenclature

PARSEC	Percussive And Rotary Surveying & Extracting Carousel
MOLE	Martian Overburden Layer Excavator
WOB	Weight On Bit
MELT	Melting & Extracting Liquid Tool
CAT	Core Analysis Tool
PLECOS	Potable Liquid Extraction & Cleaning Osmosis System
RO	Reverse Osmosis
ROS	Robot Operating System
BITE	Background Interim Terrain Estimator
CHEW	Consequent High-volume Experiential World-guesser

1. Introduction

Humanity has never been closer to establishing a permanent presence on another planet; however, for this to be accomplished, a sustainable method for obtaining water must be developed. Water is needed for sustainable extraterrestrial activity including fuel production, life support, industry, and human consumption. Northeastern University’s Moon to Mars Ice and Prospecting Challenge Team proposes PARSEC: **P**ercussive **A**nd **R**otary **S**urveying and **E**xtracting **C**arousel, to uncover, melt, extract, and purify ice from subsurface deposits on Mars and the Moon. PARSEC uses two tools to drill into simulated Martian regolith, melt out a hemisphere of ice, and extract and filter the water. A third tool will then collect samples from the overburden and construct a model of the subterranean layers.

2. Mechanical Design

2.1 Framing and Mounting

PARSEC’s framing system is composed of an I-shaped base with two vertical posts supported by 45° struts. 1.5 in aluminum 80/20 extrusion was chosen for its suitable strength-to-weight ratio and ease of customization. Internal double-anchor fasteners at the ends of each beam provide a vibration-resistant means of joining the frame. Four adjustable L-brackets attached to the base allow the system to be mounted to a testbed by inserting wood screws.

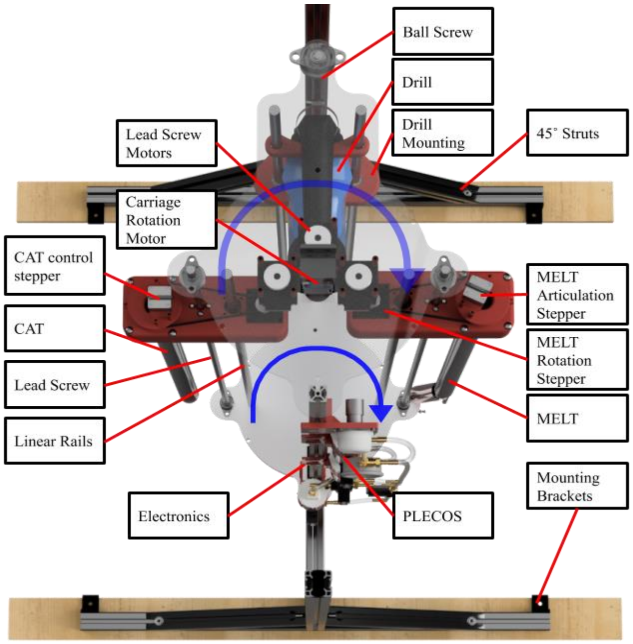

Fig. 1. *Top View of PARSEC framing and Mounting*

PARSEC forgoes the traditional horizontal rail tool rack in favor of a unique tool carousel. With this system, three tools are positioned at 90° increments along a turntable, with the electronics and filtration systems across from the drilling system to serve as a counterweight, as shown in **Fig. 1**. The melting tool and core analysis tool are placed at opposing ends of the turntable, allowing simultaneous melting and prospecting operations in separate holes. The turntable is actuated by a DC motor with a planetary gear reduction, while its position is tracked with an encoder. This motor, as well as three stepper motors, are controlled by a dedicated microcontroller to achieve the necessary rotation and translation of the tools.

2.2 Drilling Operations

PARSEC's drilling system, MOLE (**M**artian **O**verburden **L**ayer **E**xcavator), makes use of a rotary-percussive drill to quickly bore through both hard layers and compressive layers of overburden. PARSEC uses a Makita 10 A SDS-Max hammer drill in conjunction with a 1-9/16 in masonry auger providing a working depth of 30-½ in.

MOLE is mounted between two linear rails and driven by a ball screw providing smooth and precise movement. Between the ball screw and the mounting system there is an intermediary load cell for the drill, allowing for accurate measurement of weight on bit (WOB). The mounting system also includes a stabilizer for the top handle of the drill to help prevent vibrations and keep the system stable while drilling. MOLE will be controlled through its own dedicated microcontroller and will be equipped with a solid-state relay as well as a set of sensors to capture WOB and drill rotation speed.

MOLE will perform pseudo-Rockwell hardness testing to supply further data on the overburden layers for the digital core. This involves striking the desired drilling location lightly once and then again with greater force. The measurement of the displacement of the compressed material between the two strikes will provide information on the material being drilled, which may be compared to a sample database.

2.3 Melting and Extraction System

PARSEC's **M**elting and **E**xtracting **L**iquid **T**ool (MELT) aims to maximize the volume of water collected per hole by utilizing an articulating heating probe. Its arm articulates 90˚ upwards and rotates reciprocally to melt out a hemispherical sector. A pair of torsion springs enable constant contact with the ice to maximize thermal efficiency. This articulation is controlled by a miniature lead screw within the shaft of the tool, which precisely controls the slack of a wire rope attached to the top face of the melting arm. The outward torque of the torsion springs is thus restrained by this wire rope. This configuration allows for compliance to prevent damage to the probe and place continuous pressure on the ice.

The probe fits into a diameter of 38 mm, and has a fully extended radius of 200 mm, resulting in a hemisphere with a volume of 16.75 L. Two adjacent 400 W cartridge heaters are embedded along the length of the melting arm, as seen in **Fig. 2**. The heaters have a variable watt density which correlates to the respective arc length each point of the probe travels. The body of the probe will be machined out of aluminum, or copper (cost permitting), and the articulation housing will be machined from aluminum.

The stepper motors and relay for the cartridge heaters in MELT will be controlled using another dedicated microcontroller. This microcontroller will monitor the rotation, articulation angle, and temperature of the probe using a potentiometer and several thermistors. Using this data, an approximation of the volume melted can be calculated.

An extraction tube is vertically fixed to the heating probe and fits within the contour of the melting arm body. When retracted, the melting arm shields the extraction tube inlet. Water will be carried up the probe shaft and to the filtration system via flexible tubing.

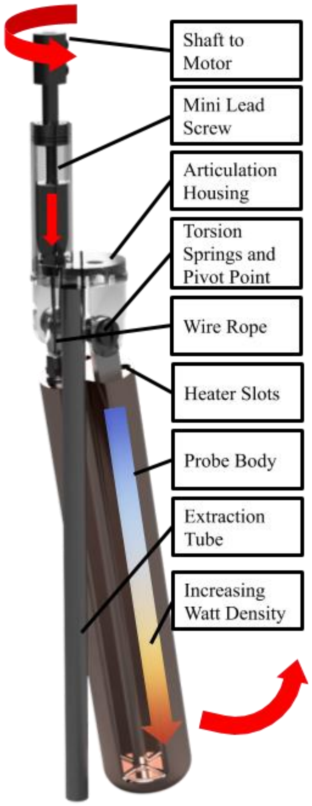

Fig. 2. *Configuration of MELT*

2.4 Filtration and Water Collection

PARSEC’s filtration system, **P**otable **L**iquid **E**xtraction & **C**leaning **O**smosis **S**ystem (PLECOS), combines two layers of filters with a two-stage reverse osmosis (RO) arrangement to produce potable water. The system uses peristaltic pumps and solenoid valves actuated by a dedicated microcontroller to move the water through each filtration chamber seen in **Fig. 3**. First, water is collected through MELT’S inlet, which is covered with steel mesh. This then passes through a chamber with a 100-micron sediment filter and a 50-micron activated carbon filter. Each chamber has a valve that can be opened to purge debris buildup.

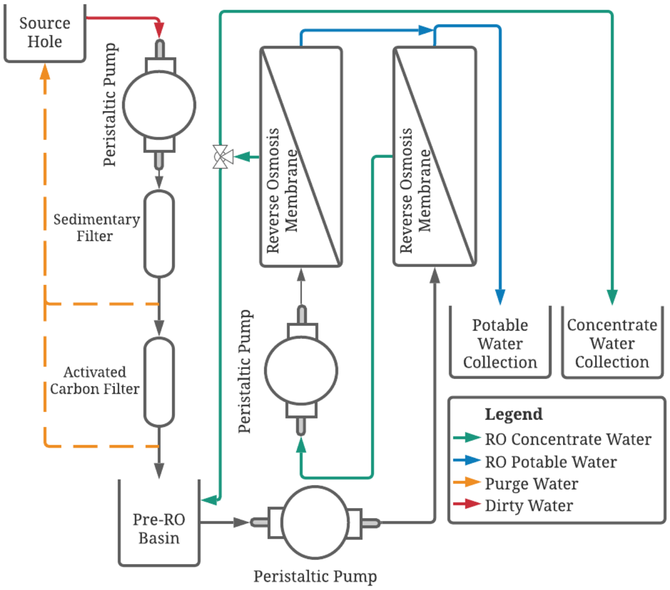

Fig. 3. *Filtration Schematic*

The filtered water then enters a holding basin before undergoing reverse osmosis. Pressure is used to force the water through a semipermeable membrane, removing any remaining impurities. Concentrate water from the first pass is then pumped through a second semipermeable membrane. The final concentrate may be released into a separate collection tank or returned to the initial holding basin to be refiltered. The permeate water from both osmosis chambers is sent to an external accumulation tank. Thus, two separate collections of water are produced: one for industrial uses, and one that is safe for drinking.

2.5 Sample Collection

PARSEC chooses to go beyond the original scope of the competition by implementing a **C**ore **A**nalysis **T**ool (CAT) to extract samples and obtain images of the overburden layers. The hole created by the drilling system provides ideal access to collect Martian regolith. CAT uses a rotary tool embedded in a shaft to grind exposed material and direct it into a small funnel, shown in **Fig. 4**. This funnel routes material into one of several collection tubes which are brought to the surface for further analysis. This can provide critical information on a Martian mission, as regolith samples could be analyzed for signs of life and concentrations of perchlorates or other contaminants.

CAT also includes a camera, which points radially outwards to allow for the visual analysis of overburden layers. By slowly lowering the tool at a fixed rate, the camera can take a vertical panorama which will be processed to measure layer heights. Additionally, the camera may be used to evaluate the condition of the area melted out by the heating probe, which will inform testing and competition strategy. Video is sent to a Raspberry Pi over MIPI, and CAT’s stepper motors and rotary tool will be actuated by an additional micro controller which will handle encoder data.

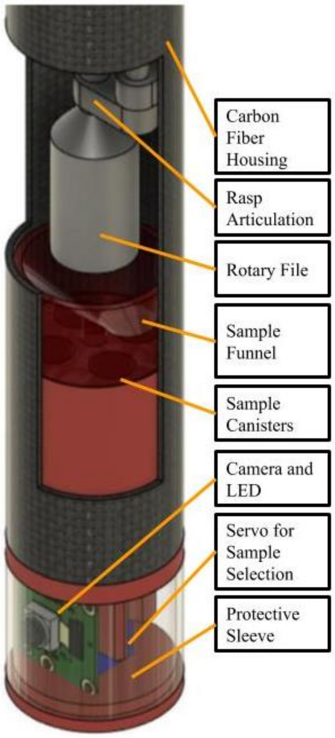

Fig. 4. *Configuration of CAT*

3. Electrical Design

PARSEC is operated through a laptop serving as a remote ground station and communicates over an ethernet cable to two Raspberry Pis. One of these is responsible for handling high-bandwidth peripherals such as USB and MIPI cameras. The other acts as PARSEC's central computer running the Robot Operating System (ROS). To interface with the hardware, the central computer is wired via shielded USBs to five custom STM32 based microcontrollers, each running the MBed OS and communicating over rosserial. The use of multiple decentralized microcontrollers allows for faster processing and a smaller overall footprint of the electronics. **Fig. 5** outlines the major hardware components and their means of communication.

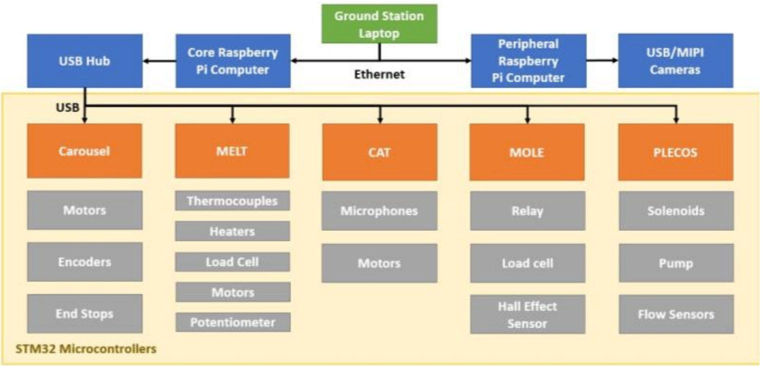

Fig. 5. *Electronics Hierarchy*

Fig. 6. *Custom Microcontroller Boards*

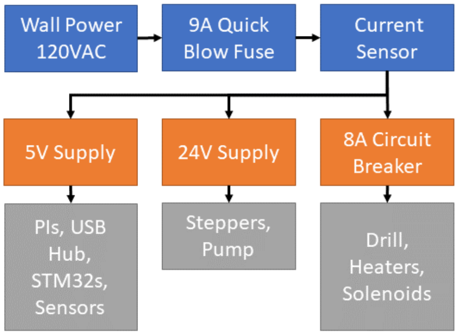

Fig. 7. *Power Distribution*

As shown in **Fig. 6**, custom STM microcontroller development boards have already been designed and assembled to allow for easy prototyping. These will be gradually phased out with the five specialized boards over the course of development, designed to streamline wiring, mounting, and modularity. Each board will have a DFU bootloader so that code can be easily uploaded via USB.

Fig. 7 outlines the overall power distribution. Power is supplied from a 120 VAC outlet and passes through a 9 A quick blow fuse followed by a current sensor. From here, 120 VAC is provided to power supplies and an 8 A circuit breaker. High voltage components that draw higher current are wired to the circuit breaker, allowing for an added layer of safety on top of software current monitoring. The 5 V supply powers the USB hubs, microcontrollers, Raspberry Pis and sensors. The 24 V supply powers the stepper motors and pumps.

4. Software Design

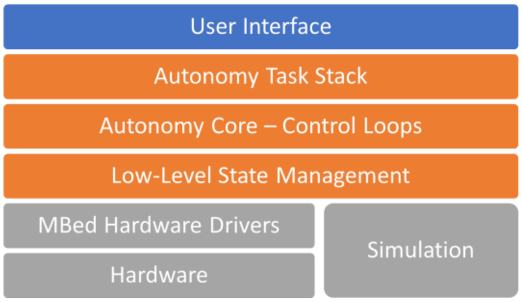

Fig. 8. *Software Hierarchy*

PARSEC's software consists of a stack of ROS nodes of increasing complexity as shown in **Fig. 8**. At the lowest level, firmware written with the Mbed OS will interface hardware with the ROS network. Above this, low-level state management of individual motors and other hardware will be accomplished by ROS action servers, receiving orders from and giving feedback to the autonomy core node. The autonomy core will run control loops on the hardware nodes to achieve a desired state, that is determined by nodes in the autonomy tasks stack. The autonomy stack will manage the high-level operations of PARSEC and log what actions still need to be performed. It will also contain the digital core, which will record and pre-process data from the instruments. The autonomy core will collect and package this data into structures that data processing models in the digital core can easily use. Both the autonomy stack and core will be connected to the Graphical User Interface (GUI), which is the top layer of PARSEC's software.

4.1 Control System (GUI)

PARSEC will be operated through a GUI on a remote ground station laptop. The main GUI, shown in Figure XX, will provide full control of PARSEC with the ability to issue high-level commands, such as starting the drilling or heating processes, while also operating lower-level mechanisms like individual motors. The GUI will be implemented fully in ROS's Qt framework and communicate directly with the core ROS network.

Accompanying the main GUI will be a live 3D rendering of the current state of PARSEC. This will allow operators to virtually observe the system and determine its current state. A preliminary design is shown in the right of **Fig. 9** utilizing the CAD models from a previous design. The rendering is handled in real time by a ROS package called RVIZ, which allows for a model that can be dynamically updated through the ROS network according to encoder and potentiometer data.

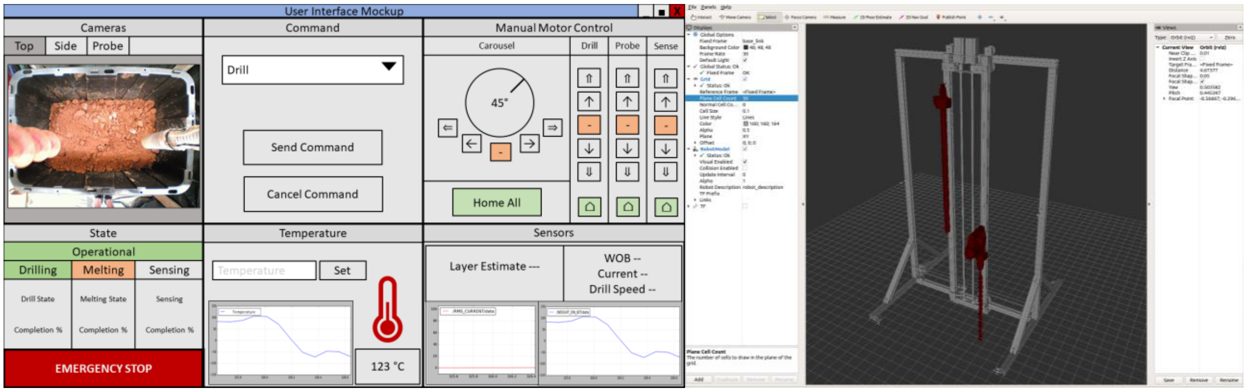

Fig. 9. *A mockup of the GUI (left) and the current progress of 3D state view (right)*

4.2 Data collection and Digital core

PARSEC will utilize a variety of instruments to gather data, which are outlined in **Table 1**. Two "supervised multi-class classification" algorithms will parse through this data for digital core synthesis. The first algorithm, named BITE (**B**ackground **I**nterim **T**errain **E**stimator), will be used to provide a live prediction of the current material to PARSEC's operator. The most promising prediction model for this application is a Hidden Markov Model (HMM). An HMM is well-suited to handle the expected inconsistency in regolith layers and fluctuations in the data, as it can prioritize keeping a consistent result.

The second algorithm, named CHEW (**C**onsequent **H**igh-volume **E**xperiential **W**orld-guesser), will run on data stored in a CSV file that is gathered throughout the entire drilling process. Its objective is to analyze a full drill operation, including contract microphone data, to determine an accurate map of material vs depth. The primary algorithm under consideration is a "k-nearest neighbors" algorithm that averages the "one vs. all" probabilities of each layer a few moments before and after the current position. This algorithm would be able to handle expected variation in data and would be resistant to frequently switching between layers. If later data from CAT contradicts CHEW, the GUI would allow for a manual override of its prediction.

Table 1. *Sensors utilized by BITE and CHEW*

Sensor	Data and application
Drill load cell	The digital core uses the acquired WOB data along with drill velocity data to determine the layer hardness.
Encoders	Encoders are used to record the positions of MOLE and CAT to determine velocity data and layer height
Current sensor	PARSEC measures the current flowing into the 120 VAC drill to calculate power consumption for predictions.
Hall-effect tachometer	A tachometer measures the rotational speed of the drill, which is expected to be useful in differentiating between solid and granular surfaces
Contact microphones	Two contact microphones measure the sound spectrum produced when drilling, as different layers are expected to produce different sounds. One is placed near the drill and another near the frame to separate sound sources.

5. Paths to Flight

PARSEC was designed for extraterrestrial use; however, a spacefaring iteration would require several changes to account for the different gravity, topography, atmosphere, temperature, and radiation levels of the Moon and Mars. PARSEC's size and mass would also have to be optimized for launch and transport. To have the most access to Martian ice deposits, a spacefaring iteration would require additional mobility provided by a rover or additional axes. The implementation of sensors such as accelerometers and laser measuring devices would further assist PARSEC in calibrating and positioning itself on uneven terrain.

The prototype construction of PARSEC is composed of aluminum, steel, carbon fiber composite, and 3D printed PLA+ plastic, which can be replaced and redesigned to reduce mass. Carbon fiber or titanium parts would make an ideal substitute for PLA+, aluminum, and steel parts due to their impressive strength to weight ratio [1]. In addition to changing materials, utilizing generative design or topology optimization would eliminate mass without compromising strength.

Since Mars has a minimal atmosphere, any devices stationed there would be subject to the ionizing radiation of space, which is capable of degrading electrical components and disrupting the crystalline structure of CPUs and diodes [2], [3]. Radiation hardened components as well as radiation shielding (made from aluminum and titanium alloys) should be used to prevent this [4]. Electronics must be further insulated from the extreme temperatures of Mars, which average about -63 °C [5]. Electronic temperature could be managed using heat dissipated from an RTG. Additionally, due to long communication times between Earth and Mars or the Moon, software developed for PARSEC should function fully autonomously.

The low atmospheric pressure and temperatures of Mars cause ice to sublimate quickly when exposed to the atmosphere [6]. Ready sublimation of Martian ice would require MELT to form a seal around the hole (perhaps via an expanding apparatus) to prevent vapor from escaping. Modifications could be made to PARSEC to transport water as both liquid and gas. On Mars it is recommended that PLECOS be replaced with a distillation system due to the aforementioned sublimation on Mars. Distillation requires a condensation process to convert the gaseous water into a usable liquid state, which could be achieved by adjusting pressure using a peristaltic pump. If the current system is kept, pressure conditions would need to be set to keep water liquid as it runs through the filters. Finally, PVC tubing currently used would have to be replaced or insulated from UV radiation which would degrade the PVC, decreasing the impact strength and making the system more prone to failure [7].

Gravity on both Mars and the Moon is reduced in comparison to earth's gravity with values of approximately 3.68 m/s^2 and 1.6 m/s^2 respectively [5], [8]. This poses an issue, as the drill forces, which can reach 150 N, could potentially surpass the gravitational force acting on PARSEC. An anchoring or tethering device would have to be implemented to the design to permit the machine to prospect without risk of dislodging.

6. Competition Strategy & Contingency Plans

PARSEC begins operations by homing its central axis and tools to ensure accurate positional data for hole selection and tool swapping. Once a hole location is selected, the drill is lowered while tracking WOB, current, position, and r/min. If WOB or current approach their maximum ratings, PARSEC will slow down drill descent or pause operations until such values stabilize.

PARSEC will execute a bite drilling method, drilling in 10 cm increments before resurfacing the drill. This incremental process reduces power consumption compared to continuous boring [9]. From here, the drill is retracted, and the tool carousel rotates until MELT is aligned. The probe then descends into the borehole, melting another 20 cm deeper before beginning to articulate. While a hemispherical sector is being fully melted, the probe will periodically extract and filter water. MELT is estimated to carve one full bowl per competition day.

On the second day CAT will be used to collect samples from the first day's drilled hole, while MOLE and MELT excavate and extract water from a new hole. Because CAT has a low power usage, PARSEC can use both the digital core tool and the melting probe simultaneously. **Table 2** outlines some possible modes of failure and the contingency plans to maintain the efficient operation of PARSEC.

Table 2. *Possible failure modes and corresponding contingency plans*

Subsystem	Possible Issues	Mitigation and Contingency Plan
General	Components are damaged	Critical components will have duplicates made for replacement in the case of a significant mechanical failure.
Drill	Drill loses rotary motion	Drill can be toggled to function only with percussive motion.
	Drill loses percussive motion	Drill can be toggled to function only with rotary motion.
Melting Probe	Probe articulation critically fails	The melting probe can continue to melt ice using the Rodwell method, melting a pocket in the ice via convection through the melted water.
	Cartridge heater fails or encounters thermal runaway	Thermistors monitor the temperature of the probe and prevent overheating. Each cartridge heater can be toggled individually.
Filtration	Buildup of debris in filtration system	The filtration system can recirculate filtered water to purge any debris clogging the system.
	Filtration system critically fails	The entire filtration system can be bypassed to extract water directly into an external accumulation tank

7. Timeline & Test Plan

The PARSEC timeline is designed to maximize time for testing and integration. All custom parts will be designed and ready to manufacture as soon as the team is notified of selection status. All stock parts will be ready to order as soon as funding is received. Components with many dependencies, such as framing and controls, are being purchased ahead of time using remaining funds from last year. The testing, design, and assembly timeline is shown in **Fig. 10**.

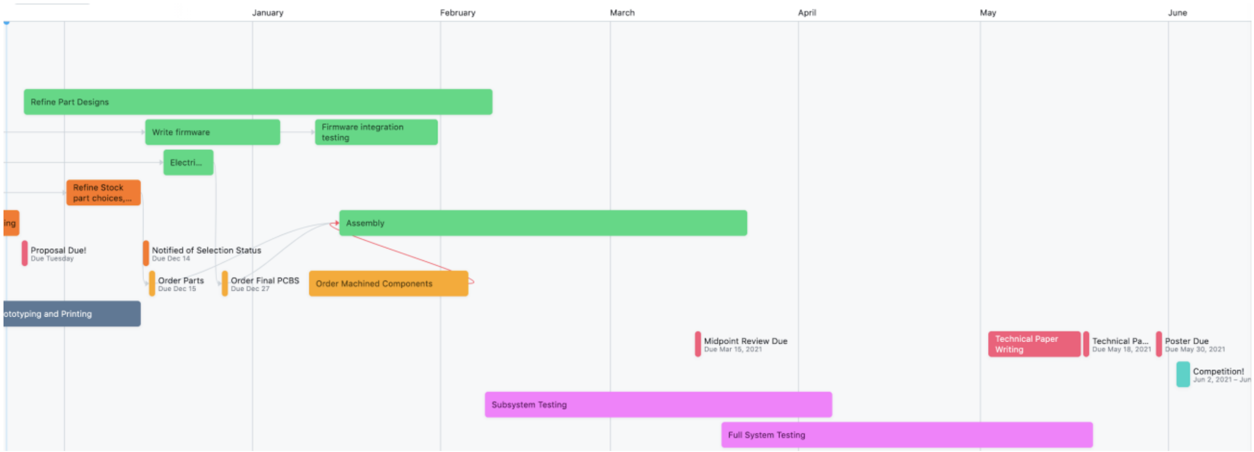

Fig. 10. *Gantt Chart Development Timeline*

Testing will follow an accelerated schedule in order to provide the software team with data to develop and test algorithms early on. Last year's system can potentially be used for collecting drilling material data as early as January. A new test bed will be assembled in January, so subsystem testing of PARSEC can commence in early February. Subsystems will be tested separately in order to begin verification early. Two months of full system testing will allow for necessary refinement and enable us to gain familiarity with operations.

8. Relevant Experience & Facilities

Northeastern University has over 4 years of experience in the NASA Mars Ice Challenge. This year's leads are experienced from last year's competition and other past projects. The PARSEC team continues to gain insight and experience from the team members of PAWES (2018), PUDLE (2019) and is composed largely of members from PRISMM (2020). PARSEC has gained new team members who have greatly strengthened our team's capabilities in manufacturing, machine learning, and robotics.

Northeastern University's Mars Ice team continues to be advised by Prof. Taskin Padir, who has supported the team since its inception, and provides great insight through his years of robotics experience. He has previous experience in RASC-AL, DARPA, and NASA Sample return. PARSEC will be built at Northeastern University, in the Richards Hall robotics workspace, RIVeR Lab, and Capstone Lab. Despite continuing restrictions on in-person gatherings, manufacturing and assembly will be able to continue in groups of 2-3 people, provided the year progresses as expected.

9. Upgrades & Improvements

PARSEC builds upon experience from our three previous competition finalists: PRISMM (2020), PAWES (2019), and PUDLE (2018). Despite some similarities, every part of the robot was reconsidered and optimized with our experience from last year. Several systems were fully redesigned based on lessons learned or a desire for new functionality.

9.1 Framing and Mounting

With prior years' linear translation systems, the service range accessible to both tools was limited to a 0.5 m line. Using a tool carousel, that surface reach is more than tripled at a 1.57 m circumference. Combined with the articulating melting arm, the carousel system can reach a 423% greater volume than previous years, fully serviceable by any of the three tools. Aluminum extrusions with rollers have been used in each previous year in combination with sliding elements, but they were bulky and prone to binding due to debris buildup. These have been fully replaced with slim cylindrical rods secured to the frame via threaded ends. These rails have half the weight and nearly half the profile, while retaining similar translatory properties.

9.2 Drilling Mechanism

The auger diameter has been reduced to allow for faster drilling and weight reduction. The mounting system for the drill has also been overhauled to eliminate binding from the large moment of the drill. The drill has linear rails on either side, which are driven by a ball screw with an intermediary load cell. The lead screw from PRISMM was switched out for a ball screw, reducing friction and thereby improving movement speed.

9.3 Melting and Extraction System

The heating probe joint was redesigned for both greater precision and compliance. There was too much backlash in PRISMM's meter-long pulley, which prevented the probe from reaching a full 90˚ and limited the accuracy of positioning. Torsion springs enable constant pressure on the ice, while a potentiometer can still maintain the active angle. PARSEC eliminates all edges which could catch on the ice and prevent rotation. The bottom face of the extraction tube will be rounded and will be covered by part of the melting arm as the probe descends.

PRISMM had to use some 3D printed plastic parts due to a reduced access to machining, which deformed under the heat. All custom parts exposed to heat will now be machined from aluminum or copper. A copper melting arm will provide a substantial improvement in thermal conductivity, which will allow for longer periods of heating without damaging the probe. The efficiency of the probe has been further improved by implementing variable cartridge heaters proportional to the arc length.

9.4 Sample Collection

PARSEC adds a completely new sample collection system, which has never been attempted by a Northeastern University team before. A freshly drilled hole provides a unique opportunity to analyze the materials of Martian regolith and to test for chemical signs of life or contaminants.

9.5 Filtration and Water Collection

The filtration system from PRISMM was mostly successful and yielded clean water, while having a means of regeneration and low power consumption. A similar approach for the initial filtration stage from PRISMM will be used in initial stages for PARSEC. Adding an RO stage will further improve the water quality and yield drinkable water.

9.6 Electrical Design

The electronics system has been redesigned from the ground up. Components including stepper drivers, relays and power supplies from PRISMM will be reused, but the layout and wiring will be completely redone. The two Arduino Megas used have been replaced with five custom STM32 based boards. These boards have internal clock speeds of up to 180 MHz and flash memory of 512 KB in comparison to the 16 MHz and 256 KB that Arduino Mega Microcontrollers have. The new custom control boards will make the electronics smaller, lighter, faster and more reliable.

9.7 Software Design

The general approach of utilizing ROS for PRISMM worked well and provided an easy way to develop user interfaces and enabled robust communication. The past system suffered, however, from a lack of manpower and integration testing. This year, the software team has vastly grown which will provide more perspectives on programming challenges and allow the full extent of ROS to be utilized.

One of the issues encountered last year was our lack of data early on. As a result, data analysis models could not be developed before hardware prototypes were finalized. To rectify this, the software team is creating a simulated system that will be able to produce data similar to what the physical system will collect, providing a way to develop and compare data analysis models.

9.8 Organization

The team also upgraded our organization, communication, and financial practices. We have established Microsoft Teams as our communication software and Asana as our project management software. Thus far, this has greatly enhanced our ability to meet deadlines, plan ahead, and ensure professional quality. PARSEC's timeline has front loaded the design work, leaving more buffer time to iterate on our design and handle any unexpected setbacks. PARSEC also has more active team members than any previous system, which has enabled our ambitious design.

9.9 Testbed Improvements

Testing could be made more analogous to Martian or lunar conditions by pressurizing the hole and altering the chamber temperature. Fans and dust could simulate the massive Martian dust storms. Layers could be slanted to simulate uneven terrain. Rather than pure sheets of ice, rocky inclusions could be incorporated. These blocks could be scattered intermittently to not guarantee hitting ice, requiring teams to implement ice searching algorithms. The system could also be forced to act entirely autonomously and make judgements about when to stop drilling and begin melting using feedback from sensors and data.

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