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# Development of an Autonomous Robot for Ground Penetrating Radar Surveys of Polar Ice

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***Abstract*— This paper describes the design and fabrication of a low cost, battery-powered mobile robot for ground penetrating radar surveys in support of Polar science and logistics. Key features of the design include lightweight construction for low resistance and high energy efficiency in deformable terrain; a passive, articulated chassis for high mobility; and design simplicity for low cost. Deployment in Greenland in spring 2008 over crevasse fields demonstrated the ability of the robot to traverse rough terrain characterized by both firm and soft snow, while gathering data from a ground penetrating radar to detect crevasses. A simple navigation and control algorithm provides low-bandwidth path planning and course correction. Mobility assessment during deployment highlights the need for non-visual means of assessing mobility autonomously. A proprioceptive sensor suite and sample data for autonomous detection of terrain traversability are described.**

## I. INTRODUCTION

Recent increases in scientific research in the Antarctic and the Arctic have led to greater demands for logistic support services. Remote scientific bases like the South Pole Station, and Greenland's North Eemian Ice drilling (NEEM) and Summit stations have historically been resupplied by air, though recent logistics efforts have focused on developing overland resupply as a more economically and environmentally efficient solution. Sub-surface crevasses, caused by shear zones in moving ice sheets, pose a serious danger to both personnel and equipment. Traverse teams currently use a Ground Penetrating Radar (GPR) unit, suspended on a boom from the front of a tracked Sno-Cat vehicle as shown in Fig. 1, to image terrain in front of the vehicle. This method gives the vehicle operator approximately two seconds of warning time to stop the vehicle after detecting a crevasse. In this paper we present the Yeti robot, a robotic platform to perform autonomous GPR surveys of polar ice. This system was designed for the purpose of crevasse detection, but could also be used for GPR-based scientific research such as meteorite detection [1] or ice stratigraphy [2]. Yeti is a four-wheeled, differentially-steered autonomous robot equipped with a proprioceptic sensor suite and a SIR-3000 ground penetrating radar unit from Geophysical Survey Systems Inc.

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Fig. 1. The Yeti robot next to the Tucker Sno-Cat. Yeti will supplement or replace the Sno-Cat for performing Ground Penetrating Radar Surveys to detect sub-surface crevasses in polar ice sheets.

### A. Related Work

Current crevasse detection methods use ground penetrating radar to isolate areas of ice with characteristic low radar reflectivity profiles [3]. The traverse teams operating in the Arctic and Antarctic deploy a radar unit from a Sno-Cat. This platform is expensive ($500,000+), slow in rough terrain, and dangerous for the operators [4].

Several alternative human-operated GPR survey tools have been developed. In February 2009, the Moon Regan Antarctic traverse will use the Concept Ice Vehicle, a propeller-powered vehicle on skis, to deploy a GPR unit in front of the traverse team. The CIV, designed by the automaker Lotus, is optimized for high speed at the cost of maneuverability over rough terrain [5].

Several autonomous robotic platforms have been developed to traverse polar terrain. Researchers at Carnegie Mellon University developed the NOMAD robot, a four-wheeled, GPR-equipped vehicle in collaboration with NASA, to autonomously search for meteorites on antarctic terrain. NOMAD has a mass of 725 kg and is about the size of a small SUV, in large part addressing the challenge of negotiating terrain features with its large size [6]. This design comes at the cost of higher power requirements, greater ground pressure, and lower safety on snow bridges covering sub-surface crevasses.

The Cool robot, designed at Dartmouth College to be used in teams to deploy networked sensors on a mobile platform for long-term autonomous data collection in Greenland. This differentially steered, rigid-chassis robot is lightweight, long range, and designed to withstand the polar environment, but is optimized for low power requirements at the cost of maneuverability over rough terrain. Results of field tests confirm the mobility limitations of such a platform over Antarctic sastrugi [7].

SnoBot, a tracked vehicle concept designed by the Cold Regions Research and Engineering Laboratory, is optimized for high mobility over soft, deep snow, where tracks offer significant advantages over wheeled vehicles or humans by distributing the robot weight over a large surface area [8]. This design is less advantageous with respect to large, discrete terrain features where such a vehicle has a greater risk of high-centering and lower ability to climb step-obstructions. In addition, tracked vehicles have large rolling resistance over flat terrain. The vast majority of terrain covered by polar traverse teams consists of flat and densely-packed snow punctuated by regions of sastrugi, making a wheeled rover more appropriate.

## II. Autonomous Radar Collection Platform

### A. Design Specifications

The Yeti robot is intended to either supplement or replace the existing crevasse detection capabilities of logistics teams operating in Greenland and Antarctica. The robot was designed to perform maximum functionality to polar traverse teams and to survive long deployments and rough handling in a harsh environment. Table 1 presents specifications for the robot.

TABLE I
Yeti Robot Specifications

| | | |
|---|---|---|
| Physical | Mass | 71 kg |
| | Power | 400 w |
| | Size | 1.1 m x 1.1 m x .76 m |
| | Ground Speed | 2 m/s |
| | Maximum Range | 16 km |
| | Communications Range | 45 km |
| | GPS Path Tolerance | 5m |
| Environmental | Temperature | -40° C |
| | Wind | 60 mph |

The robot is controlled by a Rabbit BL2600 SBC. A user can program or communicate with the robot via a serial radio modem at 115200 baud at a range of up to 45 km.

### B. Operational Model

The robot is currently configured to store GPR data on board during a survey run, after which the user can download or view the radar data. In the proposed operational model, the robot will be programmed to collect radar data along a path up to 16 km for post-processing. Bandwidth limitations of the current serial radio communications link prevent the robot from transmitting radar data back to the operators, but future work will include the addition of onboard signal processing capabilities that will allow Yeti to detect crevasses, autonomously focus its search strategy, and transmit a simplified crevasse map back to base.

### C. Polar Terrain

The Yeti robot is designed to address the needs of logistics teams that resupply the South Pole station from McMurdo in the Antarctic, or the Summit station from the Thule station in Greenland. Both of these routes are surveyed using satellite imagery and by helicopter in order to minimize hazards like sections of ice with open crevasses or ice sheer zones with a high probability of sub-surface crevasses. Based on these surveys, the Yeti robot does not have to worry about the possibility of falling into an open crevasse.

The majority of this terrain along the traverse routes is characterized by firm, packed, flat, and featureless snow infrequently punctuated with areas of sastrugi. Such sastrugi can range in size from 10cm to over 2m, creating a significant mobility issue for an autonomous robotic system. The robot's chassis and sensor suite were designed to maximize mobility in this type of terrain, and current work focuses on increasing the robot's autonomous obstacle navigation capabilities using these sensors.

### D. Chassis Design

The Yeti robot's design incorporates an articulated chassis that allows the front and rear ends of the robot to pivot independently as shown in Fig. 2.

Fig. 2. A passive pivot linking the front and back half of the Yeti robot chassis allow it to maintain four-point contact on rough terrain.

This passive joint enables Yeti to maintain four-point contact on rough sastrugi which would be impossible for a rigid-chassis rover. Testing work done with the Cool Robot, a rigid-chassis robot designed for the same environment, revealed significant limitations and disadvantages of a rigid-chassis design, including reduced traction, bearing control, and stability on rough, deformable terrain. Dynamic simulations performed using the Adams software package support these results, but are beyond the scope of this paper.

## E. Sensor Suite

The Yeti robot is equipped with a proprioceptic sensor suite, including encoders on each wheel motor, a 3-axis accelerometer, 3-axis gyro, wheel motor current, GPS, and an optical velocity sensor. Other autonomous robots in this class typically use stereoscopic cameras to enable path-planning and obstacle avoidance, but such a system is less effective for detecting features with low contrast and few hard boundaries with respect to their background. A vision-based system is also unable to detect terrain parameters, which are a key component in determining a robot's mobility over deformable terrain.

TABLE II
SENSORS

| Sensor | Manufacturer | Sensitivity |
|---|---|---|
| 3-axis Accel. | O-Navi | 1000 mV/g |
| 3-axis Gyro | O-Navi | 12.5 mV/°/$s$ |
| Optical Vel. | Corsys | $< \pm 2\%$ |
| GPS | Novatel | 1.8 m (RMS) |
| Wheel Encoders | EAD Motors | 40,000 cts/rev. |
| Motor Current | A-M-C | - |

# III. Mobility and Operational Testing

In April 2008, Yeti was deployed for testing alongside the Greenland Inland Traverse (GRIT) team. GRIT was attempting to perform the first overland traverse to resupply the NEEM and Summit stations. The GRIT team used a Tucker Sno-Cat with a 25' boom-mounted GPR unit to survey the route during the traverse.

Yeti was tested alongside the Tucker Sno-Cat to determine both its mobility limitations and its capability of autonomously collecting GPR data for the purpose of crevasse detection. These tests were also performed to assess the robot's utility as a tool to the traverse team and the system robustness in the polar environment.

## A. Mobility Testing

*1) Endurance Testing:* Mobility tests were conducted on the west Greenland ice sheet outside the Thule Air Force Base on different terrain types representing a typical survey route. The first test consisted of a 2.2 km route from the base of the ice sheet, through a field of sastrugi, and onto a snowfield, then back to the base of the ice sheet. The route was chosen to incorporate sections of ice, densely-packed snow, sastrugi, and wind-drifted loose snow. The outbound leg of the route had a consistent slope of approximately 5°. Large sastrugi features were concentrated within a band approximately 100m wide. This band of sastrugi contained features ranging in size from 20 cm to 1m pk-pk and spaces between sastrugi features were filled with ice, presenting an interesting challenge for the robot.

The Yeti robot was configured to drive this route using a simple PID controller designed to keep the robot's heading aligned towards each successive waypoint. This allowed the team to make qualitative observations of the robot's interaction with the terrain. The robot successfully completed the full route, returning to the starting position without getting stuck on either sastrugi or loose snow. Large sastrugi features could alter the robot's heading, but the controller was capable of handling these disturbances.

*2) Rough Terrain Negotiation Testing:* Manual and autonomous mode testing revealed several categories of terrain features that present a challenge for the robot as currently configured:

1) **Narrow vertical ridges** - On vertical ridges taller than 50cm with a width less than the robot's wheelbase, the robot has enough traction to bring its front wheels over the ridge, but loses traction once the rear wheels hit the feature. Such features present the greatest mobility hazard for Yeti since they are more likely than other features to cause an unrecoverable loss of mobility. Once Yeti is stuck straddling a ridge, the robot cannot move forward and often lacks enough traction to reverse and bring its front wheels back over.
2) **Loose wind-drift snow** - Loose snow can accumulate on the leeward side of features acting as windbreaks in otherwise flat and unfeatured terrain. Such patches, while often flat, can contain loose, sugary snow with very low cohesion, causing the robot to exhibit high wheel slip or to become immobilized. These areas are typically less than 10cm deep, and it is uncommon for the robot to become completely immobilized after digging in its wheels.
3) **Step obstruction** - The robot's performance in climbing a natural step-obstruction is dependent upon the snow terrain parameters and the size of the step. The robot has little difficulty climbing a 25cm step of almost any snow type, but it's performance on larger steps is limited by the interaction between the wheels and the terrain. On larger steps of 35 cm or more, the robot can easily get its front wheels over the obstacle. As the weight shifts towards the rear wheels, the front tires lose traction and dig in, preventing the robot from moving forward. Almost all such cases are recoverable by reversing direction and backing away from the step.

# IV. Autonomous Rough Terrain Negotiation

Preliminary work has been done to apply machine learning methods to enable the Yeti robot to detect immobilization and hazards frequently encountered in Polar terrain. We use a classification-based approach to identify mobility hazards and prevent irrecoverable immobility on discrete features or loose-snow using only proprioceptive sensor data. Iagnemma et al. implemented immobilization detection used a support vector machine (SVM) based binary classifier [9]. This supervised learning method attempts to replicate a human observer's ability to quickly identify immobilization using visual or auditory cues, and attempted to emulate human judgement using onboard sensors and a binary classifier to differentiate between normal driving and immobilization. This work chooses a different approach, using multi-class SVM classification to detect immobilization conditions as they begin to occur. Results of field testing show that without immobilization detection, the Yeti robot can dig itself into the surface and become fully immobilized. Detecting immobilization after it occurs is not sufficient to enable the robot to recover and continue its mission. By detecting immobilization as it occurs, the robot is less likely to dig itself into the surface, improving its chances of recovery.

Classification was performed using the PyMVPA open software suite [10]. In this work, both training and test data sets are processed offline, but it is possible to perform classification using a trained SVM in real time on an embedded system. The SVM is trained using a hand-labeled set of feature vector and label pairs $(\mathbf{q_1}, r_1), ...(\mathbf{q_i}, r_i), ..., (\mathbf{q_l}, r_i)$ where $\mathbf{q_i} \in \mathbb{R}^n$ and $r_i \in \{0, 1, 2\}$ and where $r_i$ represents the label associated with the three possible classes: 'Normal', 'Marginal', or 'Immobilized'. Data are sampled at 20 Hz and sensor measurements are used to compute elements of a 10-element feature as shown in Eq. 1.

$$\mathbf{q_i} = \begin{bmatrix} \text{Optical Velocity} \\ \text{X-Axis Acceleration} \\ \text{Wheel Resistance Torque } (4) \\ \text{Wheel Slip } (4) \end{bmatrix} \tag{1}$$

The resulting feature matrix is scaled such that each separate feature, corresponding to a matrix row, is in the range $[-1, 1]$.

The four wheel resistance torques are calculated using measured motor currents combined with IMU measurements to subtract out dynamic forces on the robot. Wheel slip is calculated as:

$$S = \frac{(R\omega - V)}{R\omega} \tag{2}$$

where $R$ is the wheel radius, $V$ is the longitudinal velocity of the wheel center, approximated by the optical velocity sensor, and $\omega$ is the angular speed of the wheels as calculated using differential measurements from the wheel encoders. The wheel acceleration is also calculated using differential measurements from the wheel encoders.

The feature matrix and corresponding data labels are used to train the SVM, and a separate set of validation data is used to test classification accuracy on the trained SVM. The SVM training performance is 95.33% and the corresponding confusion matrix is shown in Table III. Figure 3 shows one of five runs of training data used to train the classifier.

TABLE III

IMMOBILIZATION CLASSIFIER TRAINING CONFUSION MATRIX

| Predictions\Targets | Normal | Marginal | Immobilized |
|---|---|---|---|
| Normal | 333 | 1 | 2 |
| Marginal | 1 | 20 | 4 |
| Immobilized | 3 | 13 | 137 |

The generalization performance of the SVM can be tested by applying the trained classifier to a new data set. The classifier, trained on five initial runs, correctly classified 98.4% of data points in the test data set, as show in the confusion matrix in Table IV. Performance on 'Almost Immobilized' cases is lower, as would be expected given that this class will necessarily exist close to the SVM decision boundary. The definition for the 'Almost Immobilized' class is relatively arbitrary between cases of obviously immobilization and normal driving. Redefining this class to be more conservative to include cases currently classified as 'Normal' would improve the classification performance for this class.

TABLE IV

IMMOBILIZATION CLASSIFIER TEST CONFUSION MATRIX

| Predictions\Targets | Normal | Marginal | Immobilized |
|---|---|---|---|
| Normal | 216 | 0 | 1 |
| Marginal | 0 | 20 | 0 |
| Immobilized | 0 | 5 | 142 |

## V. RADAR SYSTEM TESTING

As currently configured, the Yeti robot's control system does not communicate with the radar system. The robot uses a SIR-3000 Ground Penetrating Radar system supplied by Geophysical Survey Systems Inc to collect radar data at a resolution of one scan every four inches of ground distance covered. An external data logger is used to store each radar scan and corresponding GPS data to provide spatial information.

The radar equipment employed on the robot is the same equipment used by human operators on the traverse team, though there are several concerns with respect to collecting radar data autonomously, including interference between the radar and the robot and crevasse mapping strategies.

### A. Radar Interference Testing

Close proximity between the robot and the radar antenna allows for the possibility of electromagnetic interference corrupting or adding noise to the radar data. The radar antenna operates at 400MHz and potential EMI sources include the radio communication link, DC-DC power converters, or the robot's drive motors.

Several tests were conducted to determine the extent of different forms of EMI noise in the radar data. Radar samples collected while the robot was shut off were compared to data taken while the robot was driving with its wheels suspended above the ground. The resulting data showed no interference caused by either the wheel motors or the power electronics.

The robot's communication radio, operating at 900 MHz, does create noise spikes in the radar data. This, however, is not problematic for two reasons. First, this interference is only present when the robot is transmitting data back to the user. Since the robot can be controlled without the user receiving data from the robot, the onboard radio transmitter is almost never used during a data collection run. Second, any important data like position, speed, heading, or the next goal waypoint can be sent in short packets <1ms which are unlikely to overlap with a radar scan. Radar is sampled at a

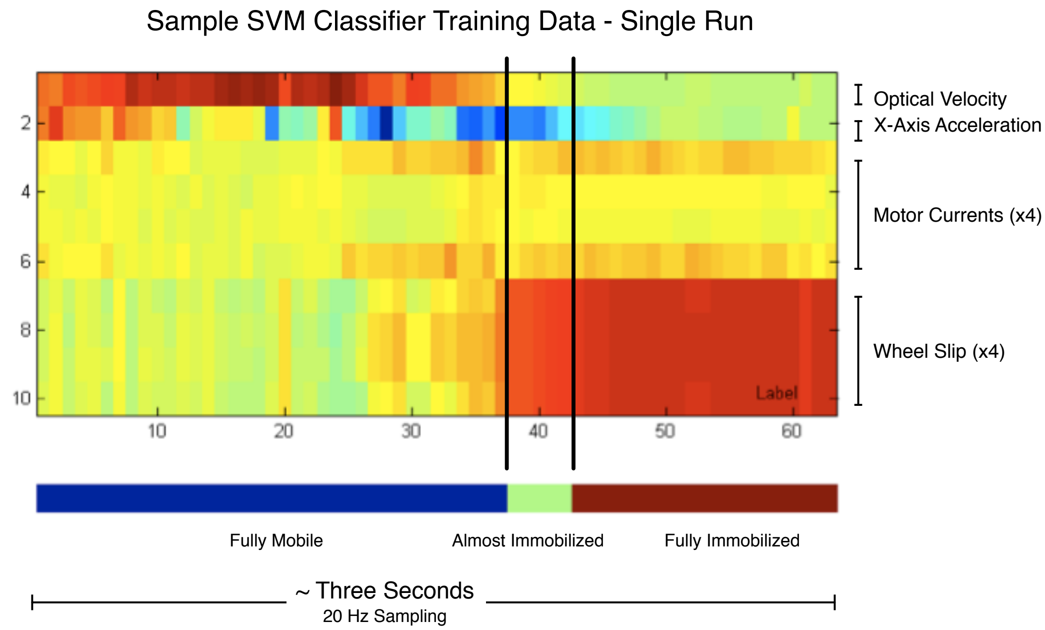


Fig. 3. Validation Dataset for previously trained SVM Classifier. Each feature vector, represented by a column of pixels in this image, is assigned one of three labels: 'Normal Driving', 'Almost Immobilized', and 'Fully Immobilized'. Feature values are scaled to normalize each feature to the range $-1$ to 1.

sufficiently high resolution such that it is highly improbable that radio interference would cause an operator to miss a crevasse when processing radar data.

### *B. Autonomous Radar Collection*

There are several differences between the current crevasse detection process and that which we propose using an autonomous radar platform. In the currently accepted technique, the lead convoy vehicle, equipped with a boom-mounted radar antenna, drives along a predetermined route using GPS to stay on track. A radar operator monitors the data and alerts the driver if he notices a crevasse. When the radar operator detects a crevasse, the team will stop and perform a local search to determine the crevasse's orientation, width, and extent, allowing the team to make a decision on whether to cross the crevasse or to find an alternative route.

A typical traverse route features large stretches of ice with few, if any crevasses punctuated with short zones with high crevasse densities. An ideal crevasse search algorithm would survey until a crevasse was found, then perform a localized search to determine more information about the crevasse. The robot is currently unable to alter its path or search strategy to focus on a particular area without being explicit programmed to follow a specific route. Future work will allow the robot to process radar data in real time, enabling it to autonomously alter its mapping strategy to focus on a detected crevasse.

Despite this constraint, the current offline radar collection system offers several advantages over a human-operated radar search. Some crevasses can have a radar signature that is extremely difficult for an operator to see if the geometry and orientation of the crevasse are inauspicious. In certain cases, the radar operator can tell that a crevasse probably exists in the vicinity of the radar antenna, but cannot determine the orientation, width, or exact location. This problem often arises due to the orientation of the crevasse with respect to the survey track. Crevasses running parallel to the track are difficult to detect but still present a danger to the traverse team. A crevasse running at a shallow angle to the survey path might be visible to the radar operator, though it may be impossible to determine its location or orientation.

In areas where radar data is insufficient to properly determine the orientation, location, snow bridge depth, or width of a crevasse, the team is forced to employ a highly conservative strategy to determine more information about the crevasse. In such a case, the team must use a hot-water drill or dynamite to open the crevasse for visual inspection. Such methods are still dangerous and can take many hours, significantly slowing the traverse team's progress.

The Yeti robot has a lower ground pressure and lower total weight than the Sno-Cat or another human-operated vehicle, allowing it to more safely access marginal terrain. In addition, an inexpensive autonomous robot does not have the same safety considerations as a larger vehicle and can be used to implement a less conservative search strategy. The Yeti robot can be used to grid-search a wide area or to approach a particular location from different headings to improve the radar signature of a crevasse, allowing the team to quickly and safely map a challenging section of the traverse route.

The current survey process endangers two human operators since operators must monitor radar screens for periods up to 10 hours, causing fatigue. In such a system, the radar operator is forced to be alert and processing radar data in real time, though the vast majority of of the traverse route

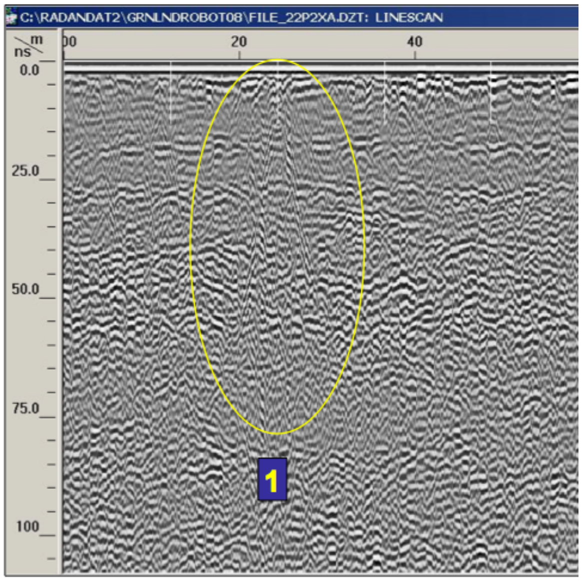


Fig. 4. A Ground Penetrating Radar image of a crevasse detected by the Yeti Robot during the Greenland Inland Traverse, 2008.

contains few, if any, crevasses. Radar data collected by a robot can be scanned for crevasse signatures faster than real time, allowing a radar operator to focus attention on challenging signatures without time pressure.

### C. Autonomous Radar Testing

The 2008 Greenland Inland Traverse team used Yeti to autonomously collect radar data in hazardous zones along the traverse route. In one test, the robot was sent in front of the traverse team over four crevasses that were previously identified using satellite imagery. Three crevasses were clearly visible in the resulting radar data, an example of which is shown in Fig. 4. It is likely that the fourth crevasse was not detected due to a temporary problem with the radar configuration and not a problem with interference. This capacity enabled the traverse team to collect data to ground truth satellite imagery in areas unsafe for human-operated vehicles.

## VI. CONCLUSIONS AND FUTURE WORKS

### A. Conclusions

In this paper, we present the design and testing of the Yeti robot, an autonomous platform for perform ground penetrating radar surveys in polar terrain. The current method of performing radar surveys for the purpose of crevasse detection in arctic terrain is slow, dangerous, and provides a limited amount of information. These limitations can, in part, be mitigated by using an autonomous robot to collect the radar data, allowing operators to safely perform grid or detailed surveys of potentially hazardous locations and allowing them to process data offline from a safe location. Mobility testing confirms the Yeti robot's ability to traverse rough polar terrain, and radar testing confirms the viability of collecting radar data from a robotic platform. Testing on post-processed data shows that a support vector machine multi-class classifier can effectively identify dangerous conditions using proprioceptive sensor data. This trained classifier can be used online to prevent immobilization by detecting an immobilization event as it begins to occur, as opposed to most current systems that detect immobilization only after the robot has lost mobility.

### B. Future Work

Future work will focus on integrating a classification-based control algorithm into the robot's control system to improve the robot's mobility over sastrugi and other rough terrain. This controller will integrate online sensor data to perform localized terrain mapping and obstacle negotiation specific to arctic terrain. Preliminary work has been done to apply machine learning techniques to identify obstacles using only proprioceptive sensor data. Integrating this information into a recovery controller will allow the robot to apply an appropriate recovery strategy in the event that it becomes immobilized.

Additional work will enable the robot to process radar data online, allowing it to autonomously detect crevasses and alter its search path.

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