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Survivability, Mobility, and Functionality of a Rover for Radars in Polar Regions

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Abstract: This paper presents the survivability, mobility, and functionality of a rover as part of a radar system for polar regions. Rovers can provide autonomy and precision for radars used to measure ice thickness and other characteristics of ice sheets in Greenland and Antarctica. These rovers can be used to move radar antennas in precise patterns for synthetic aperture radars while providing environmental protection and power to the onboard radar equipment. This paper describes the mobility, actuation, sensing, winterization, control, and virtual prototyping of a polar rover. The rover has been successfully tested in Greenland.

Keywords: Mobile robotics, robots for harsh environments, and polar robots.

1. INTRODUCTON

With the possible melting of the polar ice caps and the gradual rise in sea level, the polar regions of the Arctic and Antarctica have become key targets for earth science researchers. The potential impact from these ecological changes is still unknown. By monitoring changes to the ice sheets, researchers may be able to validate their theories regarding the long-term impact and how the ice sheets play a role globally. Due to the adverse conditions of polar environments, field research and the collection of data can be quite difficult. Rovers and uninhabited ground vehicles provide useful means for automating the collection of research data in the field by reducing human involvement. At the University of Kansas, the Polar Radar for Ice Sheet Measurement (PRISM) project [1] focuses on the task of developing a radar system capable of measuring the thickness of the polar ice sheets and other ice characteristics. To accomplish this goal, a rover is designed and developed with the goal to utilize it to operate in both Greenland and Antarctica with limited supervision (refueling and remote monitoring). In the past, robotics research has been focused on developing robust sensor suites and algorithms in order to provide reliable, precise, and safe autonomy. However, less research has been conducted regarding actuation, sensing, winterization, and navigation for robotic vehicles on an ice sheet. Equipment must be tested for operation in polar regions in order to ensure that the vehicle will have the same reliability and precision that is expected in other types of environments.

This paper describes the design and development of a polar rover [2]. The design and implementation of the rover is divided into the phases of mobile base, actuation, winterization, and sensors. A picture of the rover deployed in Greenland is shown in Fig. 1. Not only are arctic environments difficult for humans to survive in, they are difficult to navigate in, as most visible terrain is white. Construction of a roving vehicle will eliminate tasks which require people to work in the harsh climate. Such a vehicle will need to survive the weather in the arctic regions as well as protect for the equipment that it carries. A synthetic aperture radar (SAR) is used to gather as much

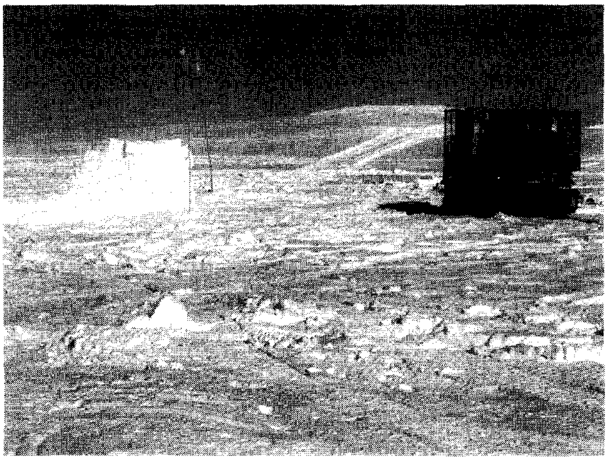

Fig. 1. The rover deployed in Greenland.

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detailed information about the bottom of the ice sheet and determine whether there ice or water at the bedrock. A SAR utilizes two sets of radar equipment, one to transmit and the other to receive. During this process a stationary antenna aims at a fixed location, while the second antenna moves in a pattern to collect a wide range of signals from the target, thus creating many data points for a single target. This acts like an antenna with the size of the area covered by the second. The down side is that it takes longer to gather data from a single point. The rover carries and positions the second antenna of the SAR system. The current stage the rover is tele-operation, but by the final stage it will be a fully autonomous vehicle. It will perform waypoint navigation, obstacle avoidance, and finally understand how to move given the assigned tasks.

2. POLAR ROVERS

2.1. Polar environment

Sensing in the polar regions can be more challenging than in more hospitable environments. Temperatures may drop well below -40° Celsius. Wind speeds may exceed 160 kilometers per hour. Equipment may be damaged as a result of these temperatures and wind speeds. Vision may be limited due to the lack of contrast on the icy surface. With this lack of depth perception, many potential natural obstacles may be over looked. For instance, sastrugies, snow drifts that form as a result of wind erosion, may have heights of up to one meter. In addition, crevasses in the ice sheet may be encountered that remain invisible until it is too late. Sensors for positioning and localization may also experience difficulties in the polar regions. Compasses are less effective due to their close proximity to the poles. GPS satellite coverage near the polar regions is reduced because the satellite network focuses primarily on more populated or strategic areas. If there are not enough visible satellites, GPS position accuracy may be reduced, or position information may not be available.

2.2. Related work

Robotics for polar environments has been studied by a number of researchers. There are several examples in which one can draw information regarding the performance of various sensors for polar environments. Dante I [3] was developed by Carnegie Mellon University's Field Robotics Center for the purpose of repelling down the steep walls of a volcanic crater to take scientific measurements at the volcano's crater lake. Dante was deployed in 1992 at Mt. Erebus, Antarctica, but failed to complete its mission due to the loss of communication capabilities with the robot. Dante I's navigation relied heavily on trinocular stereo vision and a scanning laser range finder. From initial testing and field data, it was concluded that the stereo vision was less effective when the terrain ahead lacked texture. The cost of higher resolution was often processing power. The laser range finder provided rapid retrieval of data regarding the surrounding terrain, but was sensitive to varying terrain.

Carnegie Mellon University constructed Nomad [4,5] initially for Chile's Atacama Desert in 1997. After its initial mission, it was winterized for the purpose of locating surface meteorites in Antarctica. Nomad's first mission to Antarctica's Patriot Hills revealed that stereo vision was not a viable option due to the lack of surface details. Later missions successfully utilized the laser range finder and an experimental Millimeter Wave (MMW) Radar. Differential GPS was used for autonomous navigation. Using waypoint navigation, Nomad followed a path of waypoints to explore the ice surface for potential meteorites. Based on their experimental results, it appears that GPS was a viable solution for providing navigation and heading information to Nomad.

The Robot Antartico di Superficie (RAS) [6] has been developed by the Italian National Agency for New Technologies, Energy and Environment (ENEA). The goal of this project is to automate Snowcat-type tracked vehicles in Antarctica so that they may autonomously travel along paths between field camps. The sensor selection for this robot focuses on ruggedness and redundancy. Navigation for RAS relies on both vision and Real-time Kinematic GPS. Real-time Kinematic (RTK) GPS is a special technique in which a base station determine GPS error and broadcast corrections for this error to other receivers on vehicles. The measurements from these receivers improve to centimeter-level accuracy. Whenever the vehicle is required to do more precise maneuvers such as docking or following a precise course, RTK GPS is utilized to ensure that the movements are accurate. Vision allows the vehicle to detect tracks made by previous traverses and sets a path for the vehicle to travel. A collection of inertial sensors are utilized to determine the speed and orientation of the vehicle. Accelerometers are used in all three axes to determine speed and heading. In addition, inclinometers are utilized to determine the roll and pitch of the vehicle. Obstacle avoidance primarily relies on a pair of laser range finders which produce a 120 degree scan of the area in front of the vehicle. A radar-based range finder is used solely as back up in case of LRF failure. Finally a ground penetrating radar is used for crevasse detection.

3. MOBILE BASE

The first step in selecting the proper base is to determine the requirements needed to perform the given task. The first and foremost requirement of the platform is that it should be able to drive on both snow and ice without slipping or getting stuck, while carrying maximum load. The base must operate in a temperature range of -30 to 40°C and altitudes from 0 to 3000 meters above sea level. Not only should the vehicle drive in snow and ice, but it should also handle dirt and grass, as much of the testing is performed in Kansas. It is acceptable that there be minor modifications to running in both environments, such as changing the engine's carburetor jets, but major changes, like changing ski to tires or vice versa, is less tolerable. In addition to working in a wide range of temperatures and altitudes, the base platform must be able to carry the maximum load of equipment, measured by weight, 300 kg and volume, 40U's of rack-mount space. The equipment includes the radar system, automation controls, power system, and communication equipment, a weather covering, and a human for testing purposes. In addition to these weights, the platform must also tow a large 2m by 4m antenna array that could weigh as much as 150kg. The radar antenna brings into play the turning radius of the vehicle. With too large of a radius it becomes harder to position the antenna or avoid some obstacles. Too small of a radius introduces the possibility of running over the antenna, but can be corrected through software. The last set of factors to consider comes from the time and money constraints. Cost involves more than just the "sticker" price of the base platform. Other significant expenses include the control system and the winterization. This leads into how simple of a vehicle it is. A more complex vehicle costs more to maintain, fix, and actuate than a fairly simplistic one. The ease of automation and winterization is particularly important, since the vehicle had less than year to be ready for the field test in Greenland.

There are many types of vehicles to consider. This paper looks at snowmobiles, ATVs, Amphibious ATVs, RC Tanks, and other custom vehicles. Specifications from the manufacturer of each vehicle are compared to the requirements. Many times a vehicle on its own does not meet all basic needs, but has add-ons or modifications available that can increase their capabilities, like changing the skis on a snow mobile to wheels. Snowmobiles seem to make the most sense since they are designed specifically with ice and snow in mind. They cruise through snow and ice and are one of the main types of vehicles used in polar base camps. Snowmobiles are also widely used at ski resorts. The downside to snowmobiles is that they do not work on dirt nearly as well as on snow. This problem can be corrected by using a track to wheel kit on the front ski. The automation of a snowmobile has been shown through the construction a rover from a snowmobile [7].

ATVs provide plenty of horsepower for just about any application and have been known to be used just about anywhere, and most four-wheeled ATVs are relatively inexpensive. ATVs have the opposite problem of snowmobiles that is they work best on dirt and grass, and not so well on snow. The solution is similar to that of the snowmobile; only replace the front wheels with skis and the back wheels with tracks. An electric ATV, which would provide a readily computer controlled throttle, is also an option. Numerous ATVs have been converted to rovers for surveillance and reconnaissance. The CyberATV project at CMU created Lewis and Clark as a test for distributed surveillance. The Gyphon I project automated an ATV for the purpose of a search and rescue. Amphibious ATVs are designed many terrains, including water. These unique vehicles not only go over dirt and climb steep hills, but also float. Floating is not part of the requirements, however being waterproof on the bottom also indicates that these types of vehicles will also be snow proof on the bottom. Most of the Amphibious ATVs drive by a method of skid steering. That is the move by two braking levers and a throttle. The skid steering allows for the ability to turn a on a dime, not quite in place, but very close to it. Amphibious ATVs are a second popular choice for automation. Predator from Autonomous Solutions sprays fields as part of a semi-autonomous farm. Gecko from Amdyne performs reconnaissance for the army.

An RC Tank provides a simple electric platform already complete with a way to control it. The model, AAVP7A, is an amphibious model, which will make the weather proofing part just that much easier. The big downside to this type of vehicle is that RC Tank's are usually made to smaller scale, e.g., 1:8 scale, which is a little too small for the kind of equipment and power needed for the project. However, a custom 1:4 or 1:2 scale model can be built. Since the scale needed has never been built, the specifications are not known. This means that it may not work properly or cover all of the given requirements. A custom built vehicle provides the flexibility to build any vehicle necessary to complete the job. However, custom jobs require much more time to build and are arguably more expensive. Custom jobs tend to provide the greatest successes as well as the greatest failures. With building a rover from scratch all of the design constrains can be taken into consideration and accommodated. CMU researchers have designed Nomad, a built and proven arctic explorer. Nomad's goal is to find meteorites in Antarctica. After much consideration, an amphibious ATV, the Max ATV Buffalo [8], was selected as the vehicle of choice. This choice came from a number of factors. The first is that the specifications showed that the Buffalo would perform the tasks needed. The next factor was the readily availability. After inspecting the vehicle it became quite clear, that it is simple, yet rugged, design would prove easy to automate, as well as easy to maintain.

4. ACTUATION

After having selected the Max ATV Buffalo Amphibious ATV, it had to be converted into a rover. The Buffalo is a skid steering driven vehicle. It is controlled by using two brakes and a throttle. The throttle controls overall speed while the brakes cause half of the vehicle to stop, allowing it to turn on a dime. Actuating this type of control system is fairly easy; put motors on the throttle and each of the brakes. However there is the questions of what motors and where to mount them. The question of actuation is not just a question of motors, but how to control those motors and the ability of all components to satisfy the given constraints of the system as a whole. The system as a whole comprises of the motors, the motor controllers, power supplies, and the software to run the system.

The first requirement of the motors is how much force will be required by the motors to perform their task. This is crucial as not having enough force in the motors will lead to control issues which cannot be solved by software solutions. The motors must also be able to survive the cold weather and handle water. As a safety requirement if there is to be failure in the system the vehicle should come to a stop. This means it must be possible to monitor the motors. This means that the state of the motors should be known such as whether they are currently turned on as well as their current position. From a control point of view some degree of position resolution is necessary. Current design only needs two positions for the lever motors, braking and free. Only having two positions may lead to a jerky ride, so finer control of the levers is preferable. Throttle motor on the other hand requires a finer grain of control than full throttle and no throttle as speed control is more important. Also added to this requirement is the ability for a human to override the vehicle. A human override will provide the ability to complete the task in case of sever failure of the control system. In arctic environment, it should be possible to assign a human the task of driving.

4.1. Force measurements

Force measurements are highly important. These measurements are required to determine which motors are selected for actuation. To measure the forces required to move the throttle and brake levers, we first used a crude force scale. This crude method provides a rough estimate of the force required to pull back the levers at various points. Since these forces vary, this technique helps determine an ideal point to mount the actuators. After using the initial scale, a more accurate digital force meter was used to find the exact measurements. The force meter provides better results in two ways. First, it has 0.445 Newtons (0.1 pounds per foot) resolution. Second, it can be mounted to a secured location, eliminating human error of pulling on the force meter. In all cases, the measured values were for the distance needed to apply the hand levers (brakes).

The measurements on the levers were done at three different locations. The first location, the low point, would hide any show of actuation, at the base of the lever where the levers meet the skid steering transmission. The point eliminates any rotational forces caused by lever motion. The force needed at this location is greater than 448 N, and therefore not used. The second point, the medium point, is even with the seat, at this location it is easy to simply extend from the existing seat hardware to the levers. The force at this point is a reasonable 155.7 N. The final point of measurement, the high point, is as high as would allow without interfering a human driver. This location is just below hand pull throttle control. The high point is not much higher than the medium point, but going higher helps. At this location the force required is only 111.2 N. The high location requires that a platform be built to hold the motors. It also requires there be pivot points to compensate for the rotational forces. The actuator for the throttle requires 66.7 N of force for full throttle.

4.2. Motors

In order to eliminate the possibility of frozen gears, electromagnetic motors that do not use gears to achieve their motion were considered. They work much like a monorail, using electromagnets to move an object with little if any friction. The big downside to these motors is that they need power, and lots of it, to work and hold their position. In this task, power failure turns into a plus as power failure will cause the motors to no longer hold and then the vehicle will come to a stop. The lack of resistance without power makes switching to using a human drive just a flip of a switch. The use of large power is, however a concern. The direction in which a motor puts its force is also useful. Angular force motors provide the force in a circular or angular motion. This motion is useful for the conversion because levers when pulled back move in a circle from the attachment point. Angular motion can also be converted to linear motion. A wench provides a method of doing this that converts the motion from the motor to a cable that pulls in a line. Angular force makes the most sense if placed at the attachment point of the lever, but this would also require a strong motor. The best method here is to use a wench cable attachment to connect to the levers. Linear motors apply forces in a line. This is typically done with a gearing system or like the wench with a wind up cable. This motion provides a direct method of moving the lever. The downside is that the lever's motion causes rotational forces, which act against the linear motors causing extra stress and reducing their life span. This can be over come by adding a rotational point to the motors so that they move with the rotational force instead of having it act against them. For this project the linear electromagnetic motors from LinMot are used [9] and placed at the high point. By using two pivot points the rotational forces are neutralized. The motors also provided a position feedback system of 20 μm resolution. The motors work underwater and passed temperature tests running at -30C. A picture of the rover's actuation/driving mechanism is shown in Fig. 2.

4.3. Control system

Normally a microcontroller is used to control the motors. In the case of the LinMot's they came with a controller box that was ready to receive command from an RS232 port. To send position commands to the box a GoBook rugged laptop by Itronix is used [10]. A laptop provides the ability to switch out laptops in the field. Furthermore as the system grows a laptop can easily be replaced or upgraded. The rugged part of the laptop ensures that the laptop will survive harsh conditions. The downside to using a laptop is that it requires a way to secure it down while the vehicle is in motion. Another downside is that the software must also be portable between laptops and possibly operating system. Being that the rest of the system is designed with the intent of easily changing parts and being rugged, so should the software. This being the case, java is the language of choice. Java is used because it provides a cross platform solution. This combined with Java's RMI API allows for both a local control system and a seamless remote system both with complete independence of the operating system. The software itself is based off of JAUS, but is limited to two-dimensional movement.

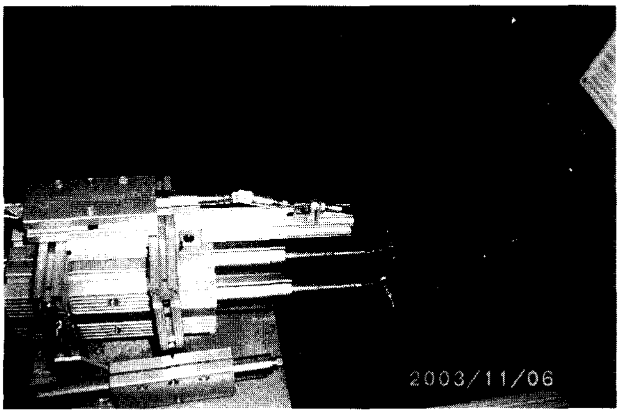

Fig. 2. The actuation and driving mechanism of the rover.

5. WINTERIZATION

The Buffalo MAX ATV provides a covering for the driver compartment, but not for the payload part. In this a shell must be designed and built to cover the back half of the vehicle and the front half. In addition to the covering there exist vent holes on the side of vehicle for air to get to the engine. These holes must be covered such that snow can not get in, but air can. The covering must provide protection against the cold and blowing snow and allow access to the inside for mounting or adjusting equipment. It should also be 80 cm high from top of the vehicle base, so the vehicle can hold 18U height worth of equipment. One idea for the shell is to use carbon fiber and form a shell to the correct dimensions. Carbon fiber provides a lightweight, yet durable protective surface. After making a scale model of the shell with carbon fiber, it is placed into a temperature chamber and tested in low temperature of -30C, and it survives several drops from a height of 1.5 m, thus proving it can survive the cold. The next issue with the fiber is how to add doors and allow for attachments of external equipment like sensors or antennas. The doors and any other openings must be planned prior to forming the mold for the carbon fiber. Otherwise the structure will not be as sturdy. The carbon fiber is also not recommended as a useful roll protection, so in addition a roll cage will also need to be constructed. Also a front windshield for the driver will need to be made out of different material, as carbon fiber is not transparent.

The second method is to construct a framework of metal and place aluminum sheets in between to protect from the snow. This metal frame solves the roll cage problem. Making modifications to the structure after its construction will not compromise the structural integrity. However, more sealing will need to be done to protect from blowing snow. The frame weights more than the carbon fiber, which could be a problem on soft snow. Metal also expands and contracts with temperature. The 0.25 cm change in the structure is negligible as the body has some flex to it. The rover uses a frame structure made out of 80/20 aluminum t-slotted extrusions [11]. The t-slotted extrusions allow for a lightweight frame with all of the structure. The extrusions also allow for easy addition of antennas and sensors on the outside of the vehicle. The design of the frame uses extrusions as a rack system, both improving the structure of the vehicle and eliminating the rack space requirement. Between the frames alucobond is used to fill in the gaps. Alucobond sheets are made by sandwiching a lightweight plastic between thin sheets of aluminum, providing light weight and structure. The edge of the alucobond is sealed with silicone gel, making all gaps waterproof. The front of the vehicle uses hyzod, which is similar to lexan, allowing the passenger to see out the front.

Two types of doors are used to allow access to the machine. Sliding doors are used on the sides and back to get to the rackmount equipment and the engine. The doors slide into gaps and are locked to prevent them from popping open while driving. The passenger section uses hinged doors. Automotive weather seals cover the gaps on the hinged doors both on the inside and outside to prevent any water from getting in. Finally the vents and exhaust areas of the vehicle need to be sealed. The vents were covered with air filters, under the assumption that they let air through, but not snow. Although this could lead to the filters clogging up with snow, the heat from the engine melts the snow and the water drips harmlessly away. The exhaust area is covered with a sheet of aluminum, which is bolted to the vehicle body. The exhaust pipe is welded to the aluminum preventing snow from getting in. The engine itself needs protection from the elements and the high altitude. The engine had a cold weather kit, which recycles the exhausts heat into the air intake and a larger air filter. The kit unfortunately did not fit with the vehicle design. The engine's carburetor jets were also replaced to accommodate for the higher altitude by adjusting the fuel-to-air ratio.

6. SENSORS

This section describes the sensor selection, sensory suite, and the sensor integration of the rover.

6.1. Sensor selection

Prior to selecting the suite of sensors to integrate with the rover, it is first necessary to determine the rover's sensing requirements [12]. The requirements may be divided into three categories:

(1) Task Requirements: Rover's mission is to complete the scientific requirements of the project. As the rover collects the radar data, it must also log the position of each measurement. The PRISM radar group has determined that the measurements must be made at centimeter-level accuracy. In addition to position information, video would also be useful during periods of remote operations and for outreach purposes.

(2) Environmental Requirements: The rover is required to function in a polar environment. Several environmental requirements must be addressed. First, the sensor must be capable of monitoring its environment in order to determine the current weather conditions and respond accordingly. The rover must also be capable of avoiding any man-made or naturally occurring obstacles (e.g., sastrugies or crevasses).

(3) Proprioception: Proprioception is the sensing of the rover's current state. The vehicle's current heading, position, and orientation are necessary for the vehicle to successfully navigate. Other properties such as current fuel level and the rover's internal temperature are also necessary.

Before beginning the selection process, a list of criteria was developed for selecting sensors for the PRISM rover. The criteria was based on a number of factors: 1) Cost: We choose to focus our attention to commercial off-the-shelf sensors in order to reduce cost. The cost of a selected sensor should reflect its overall necessity. 2) Power Consumption: Often, the output of a generator is proportional to its size and weight. Since the generator consumes both real estate and payload, sensors must be selected with minimal power consumption requirements. 3) Size and Weight: The rover has approximately 75 kilograms of payload available for sensing equipment. Internal sensors must share space with radar equipment. The space available to sensors is 75 x 60 x 90 cm. 4) Ruggedness: Sensors operating outside of the rover's heated enclosure must be capable of both operating and storing in temperatures as low as -30° C. Internal sensors must be capable of being stored at -30° C and operating at 0° C. Sensors placed on masts or antennas must be capable of surviving wind speeds up to 160 kilometers-per-hour. 5) Accuracy and Reliability: A sensor must be capable of reliably operating in any potential environment. Several sensors have accuracy requirements as well. For instance, based on specifications from the PRISM radar group, our GPS equipment must provide a relative accuracy within a few centimeters.

6.2. Sensory suite

After evaluating potential sensors, the following sensors were selected.

Topcon's Legacy-E RTK GPS System [13] was selected because of its versatility, ruggedness, and accuracy. As GPS accuracy increases, the cost of the equipment increases exponentially. However, in order to meet the requirements of the onboard radar system, this was necessary. In addition to utilizing RTK technology, the Legacy-E also utilizes signals from both United States GPS satellites and Russian GLONASS satellites. Topcon's receivers are also built rugged. The receivers and antennas are rated to temperatures as low as -40° C. The radio receivers are rated to only 0° C and will be placed inside the vehicle with an external antenna. Since the GPS receiver possesses no moving parts, its performance is not susceptible to vibration. The Legacy-E will also perform properly given the limited resources available on the rover. The receiver and radio are quite compact. The receiver's dimensions are 24.0 x 11.0 x 3.50 cm with a weight of 0.6 kg. The roving system's power requirements will be less than 3.3 Watts. The base station requires up to 35 Watts, but it will have its own power system.

The LMS221 Laser Range Finder from the Sick Corporation [14] has been selected as the obstacle avoidance sensor for ROVER. Utilizing a scanning laser, the sensor takes measurements every 0.5° over a 180° window. This particular model was selected because it has been designed to specifically operate outdoors and in cold environments. The cost of the LMS221 was quite reasonable compared to its alternatives. The use of the LMS221 greatly decreases the complexity of the obstacle avoidance system. Sonar would require multiple transducers and microcontrollers to operate and evaluate the ranging data. Other laser measurement systems require modifications in order to make the device a scanning sensor. The LMS221 integrates many features in a single unit. The ruggedness and accuracy of the LMS221 is also quite beneficial. The sensor may be stored at temperatures as low as -30° C. Using an internal heater, the sensor may also operate at such temperatures after heating to 0° C internally. The sensor's accuracy is typically 5 cm with a range of up to 20 meters.

The TCM2-50 from Precise Navigation Inc. [15] has been selected to satisfy both internal temperature measurement and vehicle orientation (roll/pitch). The unit integrates several sensors onto a single board including: a compass, 3-axis magnetometer, 2-axis tilt sensor, and a temperature sensor. The TCM2-50 will be placed inside the vehicle. It may be stored at -30 to 90° C. The operating range for the sensor is -20 to 70° C. The TCM2 sensor operates with a tilt range of ±50° for roll and pitch. The tilt has an accuracy of ±0.4° with a resolution of 0.3°. The temperature sensor has an accuracy of ±1° C and a resolution of 1°. The sensor does not utilize much of the rover's resources. The sensor consumes a maximum of 0.3 Watts to operate. Its dimensions are 6.35 x 4.58 x 3.18 cm and a weight of 45.4 grams.

The RainWise WS-2000 Weather Station [16] monitors temperature, humidity, wind speed, and barometric pressure surrounding the rover. Such information may be used to determine if conditions are safe enough for the rover to proceed. The information may also be used for educational outreach purposes. Since the weather station is required to monitor the weather outside of the rover, it is thus necessary for it to meet all of the ruggedness requirements. The accuracy of wind speed is ±4.8 kilometers-per-hour and temperature accuracy is ±0.5° C. The WS-2000 does not use much in the way of vehicle resources. Since it is mounted externally, it does not consume any of the vehicle's real estate and the sensor consumes 2.7 Watts of power.

The Pelco Esprit pan/tilt/zoom camera [17] was selected for the purpose of tele-control and outreach. This sensor may be viewed over an Ethernet connection by utilizing an AXIS 2400 Video Server. It is integrated with a pan-tilt unit capable of 360° pan and -90 to +40° tilt. It also provides a 16x optical zoom. The camera was selected specifically for its ruggedness. The camera resides within a pressurized environmental housing. It may operate at wind speeds up to 140 kilometers-per-hour and survives at speeds of 200 kilometers-per-hour. The camera is also capable of operating at a broad temperature range (-45 to 60° C). Since the sensor is externally mounted, it will not consume any real estate. The unit weights 20 kilograms. It consumes 70 Watts to operate.

6.3. Sensor integration

In this section, we will briefly discuss the placement and installation of the sensors on the rover. Next, we will discuss the software interface for each sensor. Fig. 3 shows the physical placement of the various sensors on the rover.

Calibration routines are built into several sensors that execute during startup. Other sensors such as the TCM2-50 require explicit calibration to ensure measurement accuracy. The temperature sensor on the TCM2-50 must be calibrated before initial use. This procedure involves recording several raw temperature measurements from an environment in which temperatures are known (using a temperature chamber in the lab). This works best if measurements are recorded from both the upper and lower operating bounds for the sensor. Once the measurements are completed, a simple formula is used to calculate the

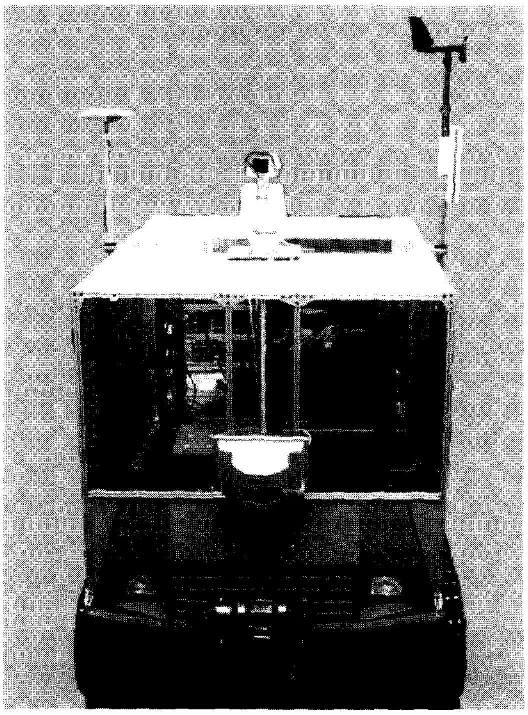

Fig. 3. The external sensors of the rover.

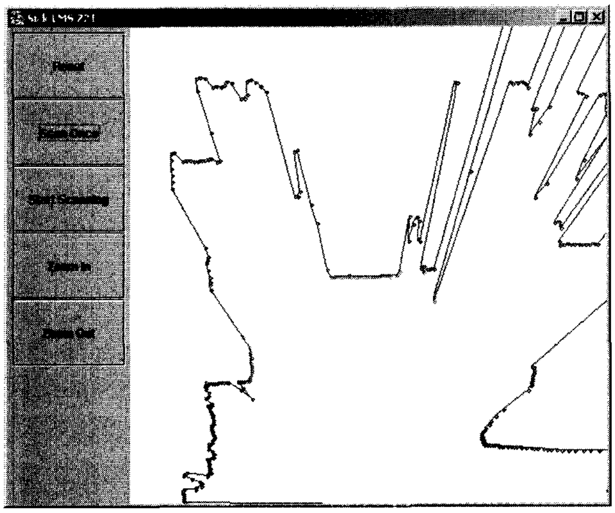

Fig. 4. The graphical user interface for the laser range finder.

calibration coefficients. These values are then stored in the device's EEPROM. The measurement accuracy is now within 1° C. The TCM2-50 was also installed internally and placed at a centralized location.

The SICK LMS221 laser range finder must be placed at an optimal height and orientation in order to ensure that the maximum visible area is covered for each scan. Unlike the other sensors that are permanently fixed on the rover, we choose to allow the configuration of the LMS221to be flexible. We are thus capable of adjusting the tilt and height of the sensor with respect to the front of the vehicle. Based on the dynamics of the vehicles motion (i.e., forward and turning velocities), certain configurations would facilitate obstacle avoidance better than others. For the GPS system, both the GPS antenna and the radio antenna were installed externally. They were placed on masts to ensure that the vehicle would not affect their reception. Both the GPS receiver and radio were installed internally. The Rainwise WS-2000 weather station was installed externally utilizing pole mounts attached to the side of the vehicle's frame. The sensor was positioned so that it's 0° (North) position would be facing toward the front of the vehicle. Using the vehicles heading, it is possible to determine the true wind direction regardless of the vehicles orientation. The Pelco Esprit camera was placed toward the center of the vehicle's roof. This placement is ideal because it may be used to monitor 360° around the rover. This ensures that the vehicle may be easily tele-controlled.

The software configuration and integration of the sensor suite was kept quite simple. Java was used to develop a software application programming interface that divided sensors into various subgroups facilitating the addition and removal of various sensors. Each sensor possesses its own datagram or ASCII packet format, which it uses to communicate with a computer interface and share data. Simple communication and control classes are developed for each sensor. Java listeners are used to receive and distribute incoming data. As a result, the overall system requires very little CPU utilization. In order to visualize the incoming data, several GUI windows were also developed. For the LMS221, a GUI (Fig. 4) presents the detected obstacles in a grid representing the area in front of the vehicle. For the GPS, the current position can be plotted on a Geodetic Tiff file if such an image for the surrounding area is available. Other sensors simple provide text boxes which update the currently measured values.

7. VIRTUAL PROTOTYPE

In order to evaluate a number of deign parameters of the rover, a virtual prototype of the rover was modeled and built using the MSC.visualNastran realistic simulation package [18]. Simulation of vehicles or components of vehicles have been used by researchers in order to design and improve vehicles models. Examples include simulation environments for track-driven robots [19], modeling of a snow track vehicle [20], simulation of a three-wheeled all terrain vehicle [21], modeling tracked vehicles using vibration modes [22], simulation of the Hybtor Robot [23], virtual prototyping of the suspension system of an all terrain vehicle [24], and the Khepera robot simulator [25,26].

Simulation experiments were performed to answer specific questions about the performance of the rover. Fig. 5 shows a virtual prototype of the polar rover. These parameters included the maximum slope the

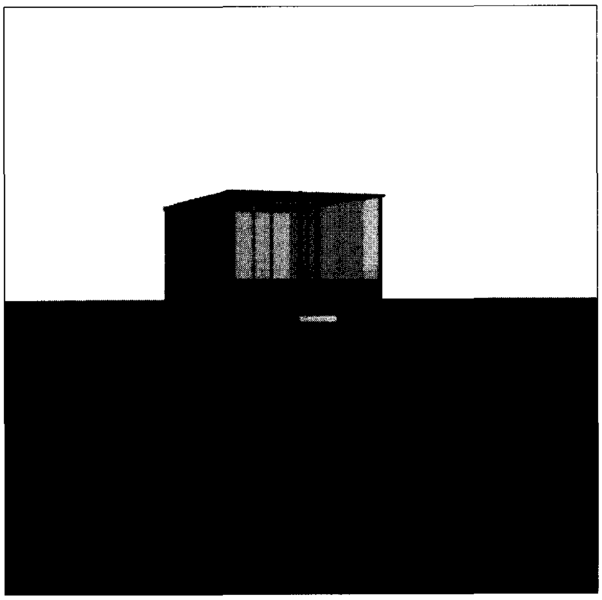

Fig. 5. The virtual prototype of the polar rover.

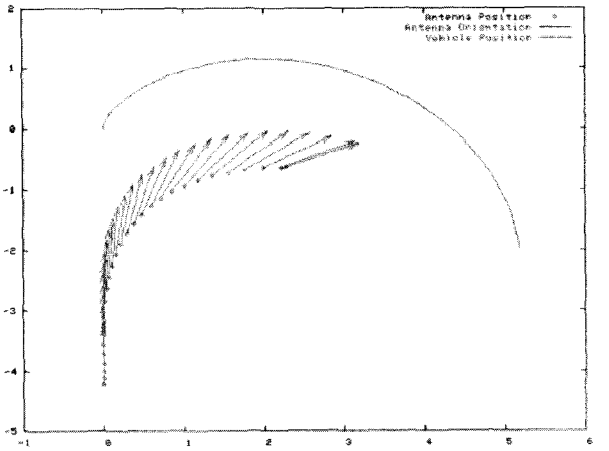

Fig. 6. The turning radius tests with a towed antenna

rover could climb (the pitch angle), and the point at which the rover might roll over (the roll angle). Another series of tests focused on how the rover handled while performing basic movements with different payload configurations. The antenna experiments were performed with different antennas, different towing mechanisms, and at different speeds. The results of a turning radius test with a towed antenna are shown in Fig. 6, with a sample of the model pulling an antenna at the speed of 10 kilometers per hour. The positions of the antenna and rover are shown, as well as the orientation of the antenna. This gives a good indication of the required distance the turn required, and how well the antenna turned around.

8. CONCLUSION

Initially an ATV park was used to test the rover. The first test consisted of putting the rover unchanged through its paces on in the park at 40C temperature for 8 hours. The vehicle was then taken back to the lab. Forces were then measured and determined that 111.2 N was needed for levers and 66.7 N for the throttle. The frame was built and stress tested. At this point it was realized that more corner pieces were needed for maintaining a solid enclosure. Finally the laptop and motors were mounted and joystick control tested with the vehicle off. After a 24 hour testing period using full force, nothing failed. The remote control was then tested with vehicle off. Finally tests moved back to the ATV park for turning and remote control tests. Everything went as planned, with both power and communication failures the vehicle came to a stop.

During the summer of 2004, the PRISM team traveled to the North GRIP research camp (75.1 N, 42.3W) in Greenland for field experimentation. A picture of the rover in the field is shown in Fig. 7. The rover survived shipping and all seals were intact, no snow accumulated inside the vehicle over a two-month period of sitting on the ice. Starting took some warming up as the vehicle battery had drained during the wait. After starting, the vehicle performed just as it had on the dirt. The next two weeks consisted of constant driving and sensor data gathering for future automation. During the driving, some of the automotive weather stripping fell off. For the most part anything that used glue or tape did not stay on, and eventually lead to snow getting inside. The snow did not affect the performance of the vehicle; it just added a little more weight when it melted. Turning in the snow was not a problem; tight turns could cause the vehicle to slowly bury itself in soft snow. Tight turns are not a problem as they also result in running over the antenna and so will be avoided. In a final test a mock antenna and rackmount computer were added to simulate the radar. The rover had no difficulty towing the antenna on the polar terrain.

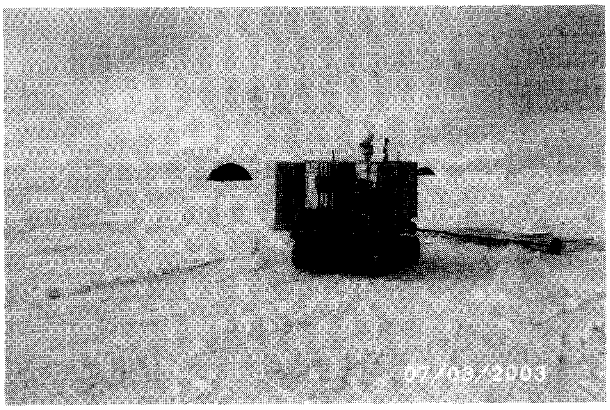

Fig. 7. Rover during field experiments.

During this field experiment, we were given an opportunity to validate the performance of the vehicle and its onboard equipment. Each sensor was tested thoroughly both individually and while integrated. In this section, we will discuss our goals for the experiments, the specific details of the experiments, and the results of the experiments. In addition to the experiments discussed in this section, data collection was extensively performed while in the field. In particular, we collected data simultaneously from all sensors while approaching potential obstacles. This data will be utilized for obstacle avoidance techniques. With only a limited opportunity for field experiments, it was vital that we carefully defined the goals of our experiments: verify proper operation of all sensors in polar conditions, determine the communication link range for the GPS radio link, and examine satellite visibility and GPS accuracy in polar region.

8.1. Evaluation

In this section, we will briefly discuss several of the experiments performed while in the field. In the Equipment Operability experiments, each sensor is

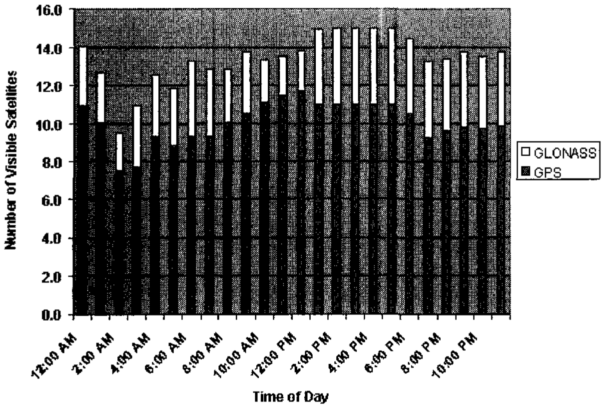

Fig. 8. Satellite visibility at Greenland's North GRIP.

tested individually. Utilizing our software interface, we confirm that the sensor is operating correctly in the polar environment. For instance, for the Pelco camera, we would test the operation of the pan-tilt unit and confirm that the camera is producing video. Each of the sensors performed remarkably well in the field. Each sensor became operational with relatively few issues. A few issues are noted. The GPS equipment operated correctly with the exception of the batteries. Both the base station and the radios are battery operated. The base station would only operate for four hours in high power mode (radio at 35 Watts). The GPS radios' battery life was also greatly diminished while exposed. The LMS221 was affected by light off of the snow covered surfaces. As a result, the sensor would report data errors frequently. Once the sensor was mounted with its sun shroud, the errors were eliminated.

For the GPS Satellite Visibility experiment, the number of visible satellites for the GPS base station were recorded for a 24 hour period. Both GPS and GLONASS measurements will be recorded. Fig. 8 shows the average number of visible satellites (both GPS and GLONASS) over a 24 hour period at North GRIP. The number of visible satellites were a maximum of 15 and a minimum of nine. During the early evening, satellite visibility was reduced as several satellites passed over the horizon. In the early morning, accuracy was also reduced. For the GPS Accuracy experiment, an area encompassed by a radius of 100 meters from the base station was utilized to determine accuracy of the GPS measurements. For each point, 20 measurements were collected over a one minute period. The standard deviation was calculated over these measurements. The resulting deviation indicates the current GPS accuracy in meters. Within 100 meters of the GPS base station, the average error for GPS measurements was approximately one millimeter. The maximum measured error was 1.8 millimeters and minimum of 0.14 millimeters.

8.2. Future work

The future work that is planned for the upcoming field seasons in Greenland as well as throughout the duration of the project can be divided into several areas including: sensor redundancy, crevasse detection, obstacle avoidance, and vehicle automation. For the 2003 field experiment, only a small suite of sensors was selected to represent the core sensor suite that would be utilized by the PRISM rover. This group of sensors is however not fixed. Additional sensors shall be included in subsequent field experiments to provide additional functionality and redundancy. While discussing potential sensors and sensing requirements, several sensors were discussed that have not been included in the current suite of sensors. For instance, sensors to monitor the fuel level of the generator and the rover have not been discussed. For this initial field experiment, such sensors were not needed because of our close proximity to the vehicle at all times. However, for future field experiments, this sensor will be included in order to include the monitoring of fuel level in the vehicle's autonomy.

Crevasse detection is a common concern for anyone operating in the polar region. Often researchers are not placed in a crevasse laden area without either a detailed map of their location, or some sort of crevasse detector. RADARSAT and prior traversals can often provide detailed information regarding the location of potential crevasses. However, it may be advantageous for us to acquire a ground penetrating radar for crevasse detection. Such issues will be further investigated. In this paper, we have discussed the selection of sensors for an Uninhabited Ground Vehicle. However, there has been little discussion regarding how these sensors will be utilized for vehicle automation, precise navigation, and obstacle avoidance. These issues will be addressed as our future work to transition the vehicle from a remotely operated vehicle to a semi-autonomous rover.

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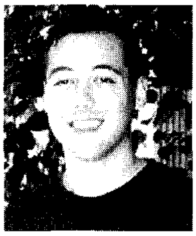

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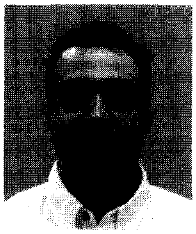

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