INTEGRATION AND EVALUATION OF SENSOR MODALITIES FOR POLAR ROBOTS

By

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ABSTRACT

As part of the Polar Radar for Ice Sheet Measurement (PRISM) project, at the University of Kansas, a mobile robot was designed constructed to support radar measurements in Greenland and Antarctica. The PRISM mobile robot was constructed using an ATV as a mobile base vehicle and building a protective enclosure to support computer and radar equipment.

This research has focused on the integration and evaluation of sensor modalities to support the PRISM rover, as well as other polar robotic endeavors. A general focus was to find commercial off-the-shelf (COTS) sensors. Given the rover's sensing needs and the prior work on planetary and polar robots, a suite of sensors was selected where each sensor met the needs of the PRISM project. The sensors were integrated with the PRISM rover. Integration of the sensors involved three main tasks of physical mounting, connectivity, and software integration. Mounting involved both external mounting of sensors as well as the construction of rack-mount cases for internal sensors. Connectivity involved connecting all of the sensors with the necessary data links so that the information is properly shared. Software integration included the development of a software API for the PRISM sensors. Sensor fusion also took place within the software to provide additional functionality.

The PRISM rover's sensor suite was next validated to demonstrate the survivability of the sensors, measure properties of the sensors not available from the specifications and data sheets, and verify correct operation, integration, and mounting of the sensor suite.

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1. INTRODUCTION

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 impacts from these ecological changes are still not well understood. By monitoring changes to the ice sheets, researchers may be able to develop and improve theories regarding the long-term impacts 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. Mobile robots provide useful means for automating the collection of research data in the field by reducing the risks due to human involvement and improving accuracy.

At the University of Kansas, the *Polar Radar for Ice Sheet Measurement* (PRISM) project [61] focuses on the task of developing a radar system capable of measuring the thickness and other characteristics of the polar ice sheets. To accomplish this goal, we are developing an autonomous mobile robot. It is our goal to utilize the PRISM rover 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, robust, precise, and safe autonomy. However, less research has been conducted regarding sensing and navigation for robotic vehicles on an ice sheet. Sensor modalities must be fully tested and evaluated for operations on the ice sheets to ensure that the robot will have the same functionality, reliability, and precision that is expected in other types of environments.

1.1 Motivation

Extensive research exists in the area of mobile robotics and sensors. This research addresses a specific application area that presents unique challenges. When designing a mobile robot for working in polar environments, special care must be taken with the selection of sensors with a focus on both survivability and reliability.

In this section, the challenges of operating in polar environments is discussed. We then provide a brief overview of the PRISM mobile robot that has been designed developed to address these challenges. An overview of the approach to address these issues is also presented.

1.1.1 Polar Traversal

Polar research often relies on data collection and traversal of the ice sheets of Greenland and Antarctica. In June of 2001, a workshop analyzed the feasibility and resourcefulness of using mobile robots similar to planetary rovers for collection of scientific data on the ice sheets [13]. This group defined several tasks with which an autonomous rover could aide, including: traverses with detailed and tedious paths, extremely remote and/or inhospitable environments, data collection parallel to a manned traversal, and data collection at slow speeds. In 2002, researchers at NASA's Jet Propulsion Laboratory proposed additional research that proposed that utilizing mobile robotics for polar exploration can provide future benefits toward planetary exploration [7].

Both groups discussed the numerous challenges that exist with polar traversals. These challenges include deep and blowing snow, crevasse detection and avoidance, sastrugi detection and avoidance, and limited supervision. Several of these challenges directly relate to the sensing capabilities of an autonomous rover, which will be addressed in this thesis, along with a number of additional challenges.

Sensing in the polar regions can be more challenging than in more hospitable environments including sub-zero temperatures and high wind speeds. Equipment may be damaged as a result of such temperatures and wind speeds.

Vision can be limited due to the lack of contrast on the icy surface. With this lack of depth perception, natural obstacles are often overlooked. For instance, sastrugies, snow drifts that form as a result of wind erosion, have heights of up to one meter. In addition, crevasses in the ice sheet are encountered that remain invisible because they are covered in snow.

Sensors for positioning and localization also experience difficulties in the polar regions. Compasses are less effective due to their close proximity to the magnetic 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 is reduced, or position information becomes unavailable.

Despite these limitations, research in polar environments has proven invaluable. For the PRISM project, the radar images that are taken of the ice are used to support glaciologists and geophysicists who address research areas such as global warming. Atmospheric researchers can utilize data collected from ice cores and other measurements to uncover the history of the planet's climate and its geological history over thousands of years. By developing a robust mobile robot for polar environments, we can uncover details that will support future research in polar environments.

1.1.2 Polar Radar for Ice Sheet Measurement (PRISM) Project

The Polar Radar for Ice Sheet Measurement project is currently underway at The University of Kansas [61]. The project's goal is to develop radar systems to measure polar ice sheet properties in order to accurately determine their mass balance and other features. Such data will help researchers determine the contributions of polar ice sheet melting to global climate change and rising sea levels.

Two radar systems have been developed for this task [23]. A monostatic/bistatic synthetic aperture radar (SAR) has been developed to generate a two-dimensional view of basal conditions of the Polar Ice Sheet. A wide-band, dual mode radar will also be utilized to determine aspects of ice sheet depth and accumulation [23].

In order accommodate these two radar systems, two vehicles have been employed. The first is a manned tracked vehicle that will tow an antenna array for the bistatic/monostatic SAR and also carry an on-board dual-mode radar. A second uninhabited rover will be utilized to carry a second SAR. When operating in bistatic mode, the rover will operate as a receiver. The two vehicles will move along side one another in a coordinated pattern. The autonomous rover will traverse a wide area along side the tracked vehicle collecting data to build the radar image.

Intelligent on-board systems are responsible for coordinating the two vehicles. Based on data received from the radars and the current state of the autonomous rover, this system will indicate areas of interest and assign autonomously waypoints for coordinated navigation.

In addition, the PRISM project has an extensive educational outreach program directed at both K-12students and the general public. The outreach opportunities also include collaboration with Haskell Indian Nations University in Lawrence, Kansas [25]. Outreach activities include maintaining a website with polar news and live updates from PRISM team members from the field [11, 61].

1.1.3 The PRISM Mobile Robot

The research presented in this thesis directly facilitates the goal of PRISM to develop a semi-autonomous mobile robot [1, 24, 56]. This robot is responsible for the transportation of the radar system and the computing equipment across polar ice sheets. It will primarily operate autonomously with the ability for a user to override the control system and operate it remotely. In the past, this robot has been also refereed to by the acronym "Mobile Antarctic Robotic Vehicle with Intelligent Navigation," or MARVIN. For this thesis, it shall be referred to as either the PRISM mobile robot or the PRISM rover.

Figure 1.1: PRISM mobile robot.

The PRISM rover, as shown in Figure 1.1, is the result of our effort [1, 24, 56]. A significantly modified version of a six-wheeled Buffalo All Terrain Vehicle (ATV)

[27] was used as the mobile base. Actuators were utilized for controlling the throttle and steering. An enclosure was constructed on top of the base platform to provide a protected environment suitable for computing equipment. To facilitate intelligent and reliable mobility, a suite of sensors were integrated to provide the vehicle with perception capabilities. These sensors will be discussed in more detail throughout this thesis.

1.2 Approach

The approach used to address the challenges related to the sensor suite for the PRISM mobile robot was performed in a number of steps. The first step involved an extensive literature search. By reviewing existing literature regarding sensors, a list of potential sensors was compiled. In addition, a literature search was performed to study existing research projects that utilize mobile robots for polar or planetary applications. By learning from the work of past researchers, some sensor modalities can be eliminated based on previously known weaknesses encountered in these environments.

The next main task was to define the criteria for the sensors that were to be selected for the PRISM rover. Project related criteria were defined such as the needs of other researchers and their equipment. In addition, the educational outreach requirements were defined. Since the vehicle will be operating in a hostile environment, environmental requirements such as operating temperature range and ruggedness were also defined. Based on the requirements defined, a suite of sensors were selected.

Upon selecting the suite of sensors, each sensor was integrated into the PRISM polar robot. A software API was developed in Java. Drivers were written for each sensor based on the API. Fusion of sensor data was also performed to create robust virtual sensors. Sensor connectivity was also addressed such that multiple sensors could be connected to a single computer. Finally, the task of physically mounting each sensor at the point where it would be most affective was addressed.

Once the sensors were integrated into the PRISM rover, series of experiments were designed and performed to evaluate the sensor suite's performance. These experiments were performed both locally at the University of Kansas and on Greenland's ice cap. These experiments were designed to verify important sensor specifications, determine the affects of locality on sensor performance, and determine any potential weaknesses that must be addressed for future field experiments.

1.3 Thesis Structure

This thesis is divided into 10chapters. Chapter 2 presents the background knowledge relative to this work. In particular, three major areas of robotic sensing: navigation and localization, collision detection and avoidance, and proprioception are presented. Sensor fusion is also discussed. Chapter 3 discusses related work in the areas of planetary rovers and polar rovers. Chapter 4 presents the sensing requirements and selection criteria used for developing the PRISM rover. Chapter 5 describes the entire sensor suite for the PRISM rover and discusses how each sensor relates to the requirements and selection criteria. Chapter 6 discusses how the sensors were integrated into the PRISM rover. Integration was divided into three areas of mounting, connectivity, and software.

Chapters 7, 8, and 9 discuss the validation of the sensor suite. Chapter 7 discusses the evaluation goals and provides an overview of experiments performed locally and during the 2003 and 2004 Greenland field seasons. Chapter 8 discusses specific experiments that were performed to validate the sensors. Chapter 9 presents the results and their analysis.

Chapter 10 concludes this thesis, presenting the contributions, limitations, and the future work.

2. BACKGROUND

This research focuses on the selection, integration, and validation of sensors for polar robots. Many sensor modalities exist to support autonomous and semi-autonomous mobile robots. The choice of sensors to integrate is problem-dependent.

The desired level of autonomy is a major factor influencing the sensor selection. A fully autonomous mobile robot must be capable of sensing its environment, interpreting the sensor data, and carrying out actions to achieve its goals. Vehicles that are teleoperated have no on-board autonomy and rely on commands from a remotely situated operator. Vehicles with supervisory control are between these extremes. They have some autonomy; however, their state is monitored remotely. A remote operator is capable of assigning new tasks, providing guidance, or temporarily taking control of the robot. The amount of control given to an outside controller is mission dependent [22].

The PRISM project's mobile robot is semi-autonomous. It operates autonomously once a set of goals is assigned. The goals can be formulated by the rover's own control system, or assigned by a human operator. A remote operator is also capable of overriding the autonomous control of the vehicle. To select sensors that facilitate the needs of the PRISM polar robot, sensors for mobile robots were investigated, along with the topic of sensor data fusion.

2.1 Navigation and Localization

A semi-autonomous mobile robot must be capable of traveling from one point to another point. Within its current environment, the mobile robot must be capable of determining its location relative to the target destination (localization). It must also be capable of determining the proper change in trajectory such that it can travel toward the destination. The sensing requirements for navigation and localization can be classified into two categories: position and heading/orientation.

2.1.1 Position Sensors

Determining the mobile robot's current position plays a dual role for the PRISM project. Intelligent navigation requires knowledge of the rover's location within the current world model. Location information could involve the precise location on a local or global map, or it could involve the distance traveled since its movement.

The robot's position also plays a role in the scientific objectives of the PRISM project. Position information is shared both with the radar and the intelligent systems. Precise positioning is necessary to form an accurate radar image.

Position is determined either locally or globally. Locally, relative positioning determines the position of the bot within a local region relative to some fixed point within that region. Globally, absolute positioning determines the robot's precise location with respect to a geodetic world model. A geodetic world model is a representation of position on a coordinate system that represents the world. For instance, Latitude, Longitude, and Altitude may be utilized. The Universal Transverse Mercator (UTM) coordinate system is another common geodetic world model that divides the Earth's surface in to grids where position is represented as x,y,z coordinates within these grids. Relative positioning satisfies the requirements of the PRISM project.

In this section, various positioning sensors will be discussed with focus on how these sensors may be used for relative positioning. The benefits and limitations of each sensor are also described.

2.1.1.1 Dead Reckoning

Dead reckoning approximates the position of the mobile robot by measuring its rate of motion and determining the relative change in its position. Dead reckoning utilizes various devices such as shaft encoders, Doppler, and accelerometers.

Shaft or quadrature encoders are some of the least expensive and simplest devices used for dead reckoning. These sensors measure the rotational rate of the vehicle's wheels or axles. Given these rates, the change in position and possibly orientation of the robot can be determined. Incremental encoders often use a photosensor to calculate the number of alternations of a pattern on a disk which rotates about the axis. Wheel slippage often results in error accumulation over time [31].

Doppler technology has been used for dead reckoning. Doppler-based sensors measure the time-of-flight of ultrasonic or microwave bursts to determine the velocity of the vehicle. Using this velocity, it is possible to approximate the vehicle's position over time. Doppler is however susceptible to interference. Its accuracy is also reduced on rough terrain where sudden changes in elevation exist [20].

Accelerometers can also be employed. The vehicle's acceleration must be doubly integrated in order to approximate the vehicle's position. Similar to the Doppler technology, this sensor does not work well on rough terrain. The sudden impacts from the bumpy road will add noise to the acceleration measurements [20].

Dead reckoning provides decent estimates, but lacks accuracy. Error accumulation may become too great, and redundancy can likely improve accuracy. For applications requiring precise navigation, dead reckoning is infeasible.

2.1.1.2 Triangulation Using Land-Based Beacons

Triangulation is a technique where position is calculated based on measured distance to known positions. For land-based triangulation, beacons or pseudolites, transmit signals using infrared or radio. The receiver uses these signals to calculate its distance to the beacons. Given a priori knowledge of a beacon's location and the measured distance from the beacon, the receiver knows its position is somewhere on a circle centered around the beacon. The circle's radius is equal to the measured distance. Repeating this technique for two additional pseudolites will result in three intersecting circles. The intersection point of all three circles represents the robot's location. Due to measurement error, a single intersection point might not exist, but can be approximated based on where the intersections of the circles are closest [20, 33].

The use of such a beacon system does however have some weaknesses. First, the range is dependent on the maximum distance that it can be away from the beacons. Second, the beacons must be placed at positions known a priori. Depending on the type of signal, line-of-sight may also be required. A land-based triangulation system is infeasible for the PRISM mobile robot.

2.1.1.3 GPS

Global Positioning System (GPS) technology has improved the accuracy of outdoor mobile robotic navigation. It is a beacon-based triangulation system on a much broader scale.

Briefly, GPS works as follows. Each GPS satellite and receiver has its own internal clock. The satellite transmits a pseudorandom signal based on its internal clock. At the same time, the receiver is producing a similar signal. As the receiver reads the incoming signal, it calculates the time offset between its own signal and the signal received from the satellite. Using the speed of light and the time offset, the distance can be obtained. Since the receiver knows the location that the satellite should be above the Earth at a given time of day (based on almanac information also sent from the satellites), a sphere of given radius centered at the satellite's position above earth can be obtained. The receiver must be located somewhere on the surface of this sphere. If the receiver repeats this calculation for two additional satellites, it finds that the intersection of all three spheres is its actual position. Additional satellites are referenced in order to provide more accurate results [26, 66].

Differential GPS (DGPS) is a technique that is used to increase the overall accuracy of GPS measurements. Traditional GPS can provide several meters of error. Multiple receivers that are close together will experience almost identical effects from the ionosphere and satellite error. If a base receiver is placed at a known location, it can compute the current error that exists with its measurements. Since other receivers in the area should have very similar error, this base receiver transmits correction values that the other receivers apply. Using the corrections, the mobile receivers know their position with about the same accuracy as the stationary receiver [5, 66].

Real-time kinematic or RTK Differential GPS is a solutions for obtaining centimeter-level accuracy. This solution provides real-time corrections to rover receivers. Like DGPS, RTK requires a base receiver at a known location. The receiver must wait longer than other DGPS technology in order to acquire the carrier phase pattern of the signals (instead of the code phase). Further, at least four satellites must be locked onto at all times. Otherwise, the receiver must reacquire all satellites before it can transmit corrections again. As the baseline (distance from base receiver to mobile receiver) increases, more satellites are required to ensure the level of accuracy needed. Due to limitations of RF technology, approximately 10km is the longest baseline allowed using FCC approved transmitters [5, 36].

There are additional ways to boost the efficiency of RTK DGPS. Dual frequency receivers virtually multiply the number of visible satellites by a factor of

1.5. GPS satellites transmit their signals at two frequencies in the L-Band (L1 at 1575.42MHz and L2 at 1227.6MHz). By utilizing both frequencies, error caused by the Earth's ionosphere can be determined and removed from the measurements. Further, GLONASS enabled receivers can also interpret position information from the Russian satellite positioning system. Receivers that incorporate dual frequency and GLONASS technology can operate with much larger baselines and maintain higher reliability [5, 17].

To obtain the absolute position of the rover, precise knowledge of the base station's location is required for both DGPS and RTK DGPS technology. The base station requires this position in order to properly calculate positioning error. When conducting research in the field, obtaining a known position necessary to establish the base station is quite difficult. Professionally surveyed points are commonly used for commercial applications such as construction projects. Such points are not often available in remote locations such as a polar regions.

If the base station's location is approximated, a precise absolute position cannot be obtained by the roving receiver, but a precise relative position can. The correction values produced by the base station possess a fixed error relative to the error at which the base position is approximated. If relative positioning is required, then this error is not a problem. For relative positioning, the approximate location of the base station can be utilized as an origin and the rover's location in x, y, and z coordinates relative to this origin can be calculated from the rover's measurements [36].

2.1.2 Heading and Orientation

The vehicle's heading and orientation are also essential for navigation. While GPS helps determine the vehicle's global position, the inclusion of a heading sensor greatly improves the ability of the vehicle to precisely navigate toward its target. The roll and pitch of the vehicle are also useful because they can be used to determine potential dangers with vehicle's instability. If the vehicle's tilt exceeds a safety threshold, it is risk of rolling over or losing control. In this section, several heading and orientation sensors are described including compasses, gyroscopes, inclinometers, and GPS.

2.1.2.1 Compasses

Compasses have been used throughout history as a heading sensor. They do, however, possess several limitations. First, since compasses rely on the Earth's magnetic field to operate, electromagnetic noise generated by the vehicle or its on-board equipment could result in an invalid heading. Also, when in closer proximity to the Earth's magnetic poles, the sensor becomes ineffective [20].

2.1.2.2 Gyroscopes

Gyroscopes have evolved from mechanically-based devices to solid-state devices. Their function has changed little. Gyroscopes have been utilized for years to determine heading and orientation for marine, avionic, and robotic applications. A single axis gyroscope provides a measurement of the rate of rotation about one axis. Three-axis gyroscopes provide roll, pitch, and yaw information. Since state information is always available, gyroscopes are capable of providing a constant stream of information.

Gyroscopes (gyros) suffer from one great shortcoming, namely, drift. Over time, the measurement accuracy drifts until the measurements become completely useless. It is often necessary to combine a gyroscope with another sensor (such as a compass or GPS) to periodically recalibrate the gyro's measurements [31].

2.1.2.3 Inclinometers

As the name suggests, inclinometers determine the sensors' current incline. Inclinometers are capable of determining the tilt in two-axes (roll and pitch).

Mercury switches have been utilized in the past to measure tilt. An array of switches are placed within a bubble containing mercury. Based on the orientation of the bubble, certain switches will be closed by the mercury. Electrolytic tilt sensors operate on a similar principal. However, a pair of probes lie within a electrolytic solution. Based on the orientation, the solution's resistance changes. An analog value indicating orientation is available in one or more axes [31].

Based on the fluid used in an inclinometer, this sensor's performances may be limited in particular environments. In areas in which there is excessive shock, or vibration, the excess motion in the fluid could distort tilt measurements. In addition, since some of these sensors have a minimum and maximum tilt range, it is crucial that these sensors are mounted properly in a position which will ensure that it is level during the default state.

2.1.2.4 GPS

One advantage of GPS technology is the wealth of information that it provides. This information may also be used to determine the rover's orientation. A signal GPS receiver can act as a heading sensor with some limitations. Additional GPS receivers can provide further orientation information with less restrictions. However, with every additional receiver, the monetary cost of the system grows.

Given two points in space, the angular difference between the two points (such as geodetic coordinates from a GPS receiver) can be calculated. This angular difference along the x,y plane represents the vehicles current heading. The angular difference along the y,z plane represents the current pitch.

When using only a single GPS receiver, the two geodetic points are obtained from sequential measurements. Whenever the vehicle first sets out, it will only have its current initial point and will be unable to calculate its initial orientation prior to moving. One situation for which this technique does not work, however, is whenever the vehicle is making a tight turn such as turning in place.

If a second GPS receiver is employed, two geodetic positions will be obtained simultaneously. Given the two point measurements, the vehicle's heading can be determined without the need for additional movement. Using two receivers, the vehicle's heading can be determined while the vehicle is turning in place.

If the receivers are placed at the front and back, the vehicle's current pitch can be obtained instantaneously. However, if they are placed on the vehicle's left and right side, roll can be calculated instantaneously. By adding a third GPS receiver, heading, roll, and pitch can all be obtained instantly. Various algorithms and techniques are available to utilize multiple receivers for attitude determination [34].

An advantage of the multiple receiver technique is that roll, pitch, and yaw is determined with incredible accuracy of within centimeters. Another advantage is that it no longer requires the analysis of previous states to determine the current state. The major pitfall of this technique is its cost. Depending on the accuracy of the GPS technology, the current price per receiver vary from $100 per receiver (10 meter accuracy) to $25,000 per receiver (centimeter accuracy) [64].

2.2 Collision Detection and Avoidance

Since most outdoor mobile robots operate in "real" environments where obstacles exist, a sophisticated collision avoidance and detection system is essential. Obstacle avoidance helps ensure the safety of the vehicle and others. In the polar regions, additional unseen hazards also exist including crevasses and sastrugis. Even if the avoidance system is quite sophisticated, it is still susceptible to failure. It is also important to include a mechanism for detecting a physical impact.

2.2.1 Obstacle Detection

Obstacle detection is the robot's first line of defense against potential collision. Obstacle detection sensors are generally grouped into one of two categories:

passive or active. A passive sensor provides information such as an image that must be processed before information regarding potential obstacles are obtained. Active sensors provide measurements with little or no processing required. Beyond determining the range of a potential obstacle, some sensors also provide details such as obstacle density and penetrability. In this section, we will discuss machine vision, sonar, laser range finders, and millimeter wave (MMW) radar for obstacle detection [20, 57].

2.2.1.1 Machine Vision

The use of image processing for obstacle detection is a common area of research in mobile robotics and machine vision. CCD cameras are passive sensors. Details such as the range to obstacles are obtained by processing the overall image. Despite the extra processing requirements, the information provided is often quite powerful.

Stereo vision is a technique employed for vision-based obstacle avoidance. Using two or more cameras, depth information can be extracted from the resulting three-dimensional image. Since this is a passive sensor, an only a single snapshot is needed to monitor the entire area in front of the vehicle. However, many of the image processing algorithms require texture within the image to fully extract range information. Snow covered areas, for instance, lack the texture details required to conclusively determine the distance to an obstacle. The accuracy of stereo vision is not as great as several alternatives; especially at greater distances.

Rather than relying on machine vision to detect the obstacles, by coupling a camera with an alternative obstacle detection sensor, additional information regarding obstacles can be obtained. For instance, the obstacle's color can determine the compressibility of the obstacle. After successive scans, ranging information from the obstacle detection sensor can determine the overall density of the obstacle. By combining this information, it could be determined whether the vehicle could safely pass without risk to the vehicle. However, such an approach is often not the safest for most mobile robots since little is known regarding what lies behind the obstacle [57].

One of the primary advantages of using machine vision for obstacle avoidance is its field-of-vision, and its depth. The sensor's range is only limited by how far the visible light can reach it. Unless installed on a pan-and-tilt unit, machine vision equipment is often entirely solid-state, which reduces the risk of failure in the field.

Several weaknesses are associated with using machine vision for obstacle avoidance. One such problem is that depth information is lost in proportion to the distance to the obstacle. Another problem is that image processing is often quite computing intensive and require a dedicated computer. Vision systems are also limited by their climate and surface conditions. If blowing snow, rain, fog, etc. is present, the information is difficult to use [20, 40].

2.2.1.2 IR Detectors

Infrared (IR) detectors can be utilized for obstacle detection. A variety of IR sensors exist and are often selected based on the application. IR or near-IR proximity detectors are capable of detecting obstacles, but are incapable of providing their distance. The proximity sensors are often made up of an IR emitter and a detector. The detector measures the intensity of the reflected IR light. If the intensity increases above a threshold, then it is presumed that an obstacle is nearby. This type of sensor does not provide enough detail for the robot to avoid small or moving obstacles [31].

IR range sensors also include an emitter and a detector. An IR emitter illuminates a spot on a potential obstacle. The detector generates an image of the spot. A function that processes the size and/or intensity of the spot generates a distance value to the spot. The sensor works for a range of about 8 to 38 centimeters [31].

IR sensors are rarely used for outdoor applications. These environments often have too much ambient IR light. In addition, the range of each of these sensors is often too short for larger mobile robots to safely avoid possible collisions.

2.2.1.3 Sonar

Sonar uses ultrasonic pulses to detect distance to obstacles based on time-of-flight. A unit's transducer emits an ultrasonic pulse. The pulse reflects off of the potential obstacle. The reflected pulse is received by the sonar unit and the time difference from transmit to receive is calculated. This time-of-flight is proportional to the distance to an obstacle [20, 31].

While the ultrasonic pulse does not travel in a straight line, it does provide only a limited area of coverage. To provide adequate ranging information for obstacle detection, a set of sonar sensors must be placed in an array. Each unit operates independently. Sonar arrays are commonly used for short range obstacle avoidance of eight meters or less.

Sonar units are relatively inexpensive; even when used in an array. Sonar are often used as an obstacle detectors for slower moving vehicles, or as a back-up for other obstacle avoidance sensors with greater range. Several disadvantages are present with ultrasonics, however. For instance, depending on interference, or angles of incidence, noise results in invalid readings. In addition, since multiple sensors are required, there is a much greater risk of failure due to the added complexity [20].

2.2.1.4 Laser Range Finders

Similar to sonar, laser range finders rely on calculating time-of-flight to determine the distance to obstacles. However, they utilize emitted laser light pulses instead of ultrasonics. By using a spinning mirror, a scanning laser range finder uniformly scans a window up to 180° with a resolution of a fraction of a degree. These sensors are known to have a maximum range up to 80 meters [55].

Laser range finders are active sensors in which they directly produce range information without any additional processing. However, a complete image of an area is not available until after the scanning has completed. For robotic applications, two-dimensional laser range finders are common because they can scan an area several times a second. Three-dimensional laser range finders, however, are often too slow for moving vehicles; especially in comparison to a passive sensor such as a CCD camera [22, 55].

In comparison with sonar, a laser range finder is much more advantageous. Since the sensor operates as a single unit, it is less likely to fail due to complexity issues. Because the laser range finder's resolution is much greater than sonar, additional details regarding potential obstacles can be obtained such as their size, density, and trajectory (if they are moving). The sensors are still incapable of determining what lies behind an obstacle. They are also much more expensive than sonar [22, 55].

2.2.1.5 Millimeter Wave Radar

Millimeter-wave (MMW) radar relies on radar imaging for obstacle detection. Electromagnetic pulses are transmitted and received to produce radar images of the area in front of the sensor. This area's width is determined by the beam width and strength of the radar.

Millimeter-wave radar outperforms virtually all other obstacle detection sensors. Since it produces radar images that must be interpreted, it is considered a passive sensor. However, by interpreting these images, a wealth of information is available. Unlike the previously discussed sensors, a MMW radar sees behind occlusions. The mobile robot's path planner robot would be better capable of planning a safe path for the vehicle. In addition to seeing beyond an obstacle, the obstacle's density can be determined [21].

Millimeter-wave radar is at the developmental stage that laser range finders were a decade ago. Most are built by experienced radar researchers and then given as a tool to a robotics project. Since they are not available commercially off-the-shelf, they can often be expensive and difficult to obtain. Since the resulting output of MMW radar is an image, increased processing power is required Another disadvantage of MMW radars is their typically larger size.

2.2.2 Crevasse and Sastrugi Detection

Researchers working in polar regions are aware of two often unseen hazards: crevasses and sastrugis. A crevasse is a trench-like rift in the ice sheet which are often very deep. Often, their tops are obscured by a thin layer of accumulated snow. Before entering the field, radar intelligence will often indicate the location of potential crevasses. However, the risk involved is often so great that it is necessary to equip vehicles with some form of crevasse detection.

Sastrugis result from wind erosion along the surface of the ice sheet. While sastrugis appear like dunes, they are actually the remaining hard snow that have not been blown away. At over a meter high, collisions with these obstacles can cause serious damage. In some instances, one side of the sastrugi is a gentle slope that leads to a meter drop-off. During blowing snow conditions, sastrugis can easily remain unseen.

In this section, we will discuss potential sensors that can be utilized to detect these obstacles. We will first discuss the strengths and limitations of the traditional obstacle detection sensors. Next, we will describe how ground penetrating radar is utilized to detect such hazards.

2.2.2.1 Traditional Obstacle Detection Sensors

Using the sensors discussed previously, only sastrugi detection would be possible. Image processing techniques would not likely be capable of distinguishing a sastrugi from normal snow. Given situations in which the sheer side of the sastrugi is facing the rover, any of the other obstacle detection sensors could detect the sastrugi. However, for situations in which the sheer side is not facing the vehicle, it becomes more difficult to detect the drop-off.

A laser range finder can be configured to detect sudden changes in elevation. One approach is to tilt the sensor downward slightly, and monitor the distance to the ice. If this distance suddenly changes, a potential crevasse or sastrugi could be present. Another alternative is to use a second laser range finder and tilt it vertically so that the scanning occurs along the vehicle's path and not across it. This technique would likely work better because it would not impact the ability to detect normal obstacles.

Computer vision techniques also exist for negative obstacle detection. Stereo vision has been used traditionally for such techniques; however, the lack of surface contrast often renders this technique useless. Thermal imaging has also been utilized for negative obstacle detection. This technique, however, has not been tested on a polar ice cap for detecting crevasses [37].

2.2.2.2 Ground Penetrating Radar

Ground penetrating radar (GPR) includes a very broad variety of radar systems. A common approach for researchers working in the field or traveling in vehicle convoys in crevasse laden areas is to place the GPR on a mast in front of the vehicle. Often the radar is integrated with some sort of vehicle control system so that the vehicle would stop immediately upon detection of a crevasse. Such systems are available as commercial off-the-shelf sensors, however, due to a lack of demand, these sensors are often prohibitively expensive depending on the budget allocated for the mobile robot [3].

2.2.3 Collision Detection

As with any technology, failure of the obstacle detection is a possibility. If a collision does occur, it is important that the impact is detected and the location of the impact on the vehicle is determined. Upon impact, it is essential that the vehicle stops moving in the direction of the impact and that it evades further damage. In this section, we will discuss potential collision detection sensors.

2.2.3.1 Bump Sensors

Bump sensors are one of the least complicated sensors available. Micro-switches turn from off to on while the vehicle comes in contact with an obstacle. Bend sensors can also be used. As the sensor bends, its internal resistance changes causing the output voltage to change [31].

For impact detection, a vehicle is often surrounded by an array of bump sensors. Such an array is either multiple individual sensors, or the inclusion of a "skirt" around the vehicle which would trigger the bump sensors if struck. For smaller mobile robots, bump sensors are quite convenient. However, for larger vehicles, the sensors are too fragile for the vehicle's high rate of speed.

2.2.3.2 Accelerometers

Accelerometers measure the g-force acceleration, when integrated within a vehicle. Not only can it be utilized to determine the vehicle's position, it can also be used to detect impacts. Given the force of an impact, the accelerometer's force measurement would suddenly change. Based on this change, the precise position of impact on the vehicle is measurable.

There are advantages to using accelerometers instead of bump sensors when constructing large mobile robots. Accelerometers provide coverage of the entire vehicle through a single unit, reducing complexity. Second, an impact will not damage the accelerometer unlike a bump sensor. Finally, by determining the precise direction of the impact, the vehicle's control system can more easily determine the correct course of action to recover from the impact.

2.3 Proprioception

Proprioception is a robot's ability to determine its own internal state. In general, these sensors inform the on-board control system and/or the remote operator of the vehicle's current conditions and bring attention to any adverse conditions. For instance, if the vehicle's fuel level is too low to complete the current mission, it would transmit a warning. These sensors are also applicable to outreach activities, providing details such as the internal and external climate information. In this section, common proprioception sensors will be discussed.

2.3.1 Fuel Sensors

Fuel sensors are a necessity for any autonomous vehicle that utilizes any type of fuel source. If the vehicle operates using a gas-based fuel, a tank pressure sensor could easily determine the amount of fuel available within a tank.

Gasoline and diesel vehicles utilize a sensor known as a fuel sender. The fuel sender utilizes a floating device connected to a potentiometer. As the level of fuel changes in the gas tank, a different output voltage is transmitted by the sender.

2.3.2 Power Levels

Monitoring power levels within a vehicle is also important. If the vehicle is purely electric, the monitoring of its internal battery is essential. Furthermore, it is important to ensure that all control systems are receiving the proper power supply. A failure of any one system could have a negative impact on the entire vehicle's operation. If the vehicle utilizes electric motors, measuring the current going to the motors can indicate if the vehicle is stuck. As the stall current rises, the probability that the vehicle is stuck increases [31].

2.3.3 Internal Climate

The internal climate within a vehicle is also important. Climate conditions that often must be monitored include temperature and humidity. If temperatures and humidity rise or fall below certain a threshold, the vehicle's mechanical, electrical, and computer systems risk failure. Temperature sensors are an inexpensive and simple sensor to detect the vehicles current temperature [31].

2.3.4 External Climate

Monitoring conditions of the vehicle's external climate is beneficial both to monitoring the health of the vehicle, and for also educational outreach. Sensors and weather stations have already been developed to measure temperature, humidity, wind speed, wind direction, and barometric pressure.

A change in any of these climate conditions could indicate that adverse weather is approaching. When operating an uninhabited in the field where weather reports are often not available, such data is essential to determining the survivability of the vehicle given these conditions.

Educational outreach is another goal for PRISM researchers. When operating in remote and interesting (including very cold) locations, up-to-date climate information is often considered data that can be presented and appreciated by individuals of all ages. By monitoring and presenting environmental conditions such as temperature and wind speed, the potential interest in the research project grows as well.

2.4 Sensor Fusion

Sensor fusion involves the manipulation and integration of data from multiple sensors in order to form a coherent individual perception. The data can be complimentary in which the fusion of data could provide additional detail. In some situations, however, data from multiple sensors may be contradictory and would require additional processing prior to forwarding the data to the control system [41].

2.4.1 Algorithms and Approaches

Sensor fusion, however, is often utilized without any ties to neuroscience. Heading and position determination often involves the fusion of multiple sensors (GPS, gyroscopes, tilt sensors, compasses, etc.). Obstacle avoidance is another area in which sensor fusion is quite common. Detection sensors can be applied in parallel, such as laser range finders, sonar, and image processing. Rather than have the control system interpret each individual sensor's data, it is useful to fuse the data into one coherent view of the world.

Many algorithms have been developed to help fuse data from multiple sensors together. Some of these methods are based on traditional methods already utilized for artificial intelligence [35]. These algorithms can operate on the levels of data representation including the signal level, the pixel-level, and symbolic-level.

Signal-level algorithms focus on directly processing the raw signals provided by each sensor. One simple algorithm that is commonly used is weighted averaging. As data from each redundant or complementary sensor is received, its data is multiplied by a weighted average. This average is determined based on the application. Kalman filters are capable of recursively forming statistically optimal estimates [35].

Pixel-level methods involve processing of images. There are numerous methods of fusing vision data, including: logical filters, morphology, image algebra, etc.

Symbolic-level methods involve fusing percepts that have already been converted to a symbolic representation. These methods often involve resolving uncertainty among sensor observations such as Bayesian estimation and Dempster-

Shafer theory. Fuzzy systems are also utilized to fuse data at the symbol level. Other approaches include the use of artificial neural networks [35].

2.4.2 Neuroscience and Behavior-based Robotics

Sensor fusion has strong ties with neuroscience in particular cognition and reasoning. Robotics researcher who work in the area of behavior-based robotics often draw connections between robotic behavior and existing knowledge of behavior from neuroscience. Behavior-based robotics involves very little global representation. Rather, percepts often directly correspond to a behavior, e.g. subsumption architecture [12]. When sensor fusion is applied to form a coherent percept, they can be encoded such that they are focused on a primitive action [4, 41].

2.4.3 Sensor Fusion for Visualization and Mobile Robot Tele-operation

Besides fusing data for mobile robot automation, sensor fusion also plays a useful role in data visualization [38]. In particular, the algorithms described previously can be applied to simplify the data prior to presenting it to the user.

When a mobile robot is being controlled remotely, the operator must interpret all of the data being presented in order to choose where the robot has to go and how to get there. By reducing the amount of data presented from redundant or incomplete sensor data, sensor fusion reduces the mental load of a human operator [38].

3. RELATED WORK

Before sensors are selected for the PRISM autonomous rover, it is important to examine existing robots designed and built for planetary exploration and polar environments. The failures and success of these robots will provide justification for or against particular sensor modalities.

3.1 Planetary Rovers

Planetary rovers provide a model for the design of polar rovers, as they also deal with harsh environments. Challenges faced by these robots are often atypical of traditional mobile robots. In this section, we will briefly discuss the challenges that planetary rovers face. Next, two of NASA's Jet Propulsion Laboratory's [32] planetary rovers will be discussed.

3.1.1 Challenges

Researchers at the Jet Propulsion Laboratory acknowledge that planetary rovers and their systems face numerous challenges that do not exist for typical mobile rovers [67]. The mobile robots are designed to be transported by space crafts. As such, they are limited in size, mass, and power. No direct human intervention is possible to repair a failed system on the rover. Further, since these rovers have scientific objectives, the sensors to facilitate these objectives have higher priority than the sensors that are responsible for navigation, obstacle avoidance, and proprioception.

Sensor selection requires great care. It is crucial that these vehicles are designed such that each sensor can possibly play multiple roles. For instance, a camera can operate both as a science sensor as well as a sensor to facilitate autonomy. In addition, solid state sensors are often considered by researchers as preferable because they lack moving parts which are more likely to fail.

A key limitation to planetary rovers operating on non-terrestrial worlds is the lack of the Global Positioning System. A GPS and communication satellite network for Mars has been considered, but often thought of as prohibitively expensive. Approaches using pseudolites or ground-base beacons that function identical to GPS have also been considered. However, this adds additional complexity since its difficult to determine the relative positions of each beacon relative to one another [33, 67].

3.1.2 Field Integrated Design and Operation (FIDO) rover

The Field Integrated Design and Operation (FIDO) rover was developed at NASA's Jet Propulsion Laboratory as a prototype for the Athena Mars Exploration Rovers (MERs) Spirit and Opportunity that landed on the Martian Surface in early 2004 [52, 68]. The rover also acts as a testbed for future rover technologies.

FIDO is equipped with a sophisticated suite of sensors for navigation and localization. On its sensor mast, a panoramic camera is utilized so that researchers can determine areas of interest and set waypoints. A stereo camera pair is located on the mast to aide in navigation to a given point. Using these cameras, the rover periodically updates its absolute vector to the target. To avoid obstacles, two HazCams used to detect obstacles are attached to the front and rear of the vehicle made up of a pair of cameras for stereo vision. An inertial measurement unit is also utilized to determine the current orientation of the vehicle [52, 68].

Several custom sensors are also developed to aide the rover. One such sensor is a heading sensor that utilizes the position of the sun relative to the rover in order to determine its absolute heading relative to true north. The sensor utilizes as CCD camera. The images from the camera are filtered such that clouds and any other atmospheric conditions are eliminated. The elevation and the azimuth of the sun are then calculated. From these measurements, heading information is obtained [65].

3.1.3 Sample Return Rover (SRR)

The Sample Return Rover (SRR) represents the future design of planetary rover for Mars [68, 52]. Many of the systems integrated into SRR were first developed from FIDO. Likewise, some of the new innovations developed from SRR are later integrated into FIDO. As the name suggests, this rover not only performs scientific experiments on the Martian surface, it also collects soil and rock samples and transports the samples to a return ascent vehicle.

Instead of possessing a sensor mast, SRR is equipped with an articulable arm. A color camera is located on the arm. At the arm's elbow, a black and white CCD camera is utilized to track the rover's target. Encoder wheels are utilized to dead reckon the vehicle's position.

Much of the autonomy development for SRR has focused on the rover's ability to locate and move to the ascent module in order to deposit its payload. This involves both line-of-sight and non-line-of-sight navigation to the lander. Once line-of-sight is made, visual tracking is possible, but until then, the rover must rely solely on dead reckoning [52, 68].

3.2 Polar Rovers

Polar rovers are mobile robots with many common features with the planetary rovers. Some of the challenges presented to planetary rovers are reduced or eliminated from polar rovers during terrestrial operations. These rovers are not as limited in size and mass. Further, if the vehicles have limited supervision, power requirements are greatly reduced. However, other factors such as blowing snow and high wind speeds create new challenges. We will briefly describe a number of polar rovers and their on-board sensor modalities.

3.2.1 Dante I

Dante I [69] 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.

3.2.2 Nomad

Carnegie Mellon University constructed Nomad [2, 21, 40] 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 appeared that GPS was a viable solution for providing navigation and heading information to Nomad.

3.2.3 Robot Antarctico di Superficie - ENEA

The Robot Antarctico di Superficie (RAS) [10] was 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 can 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.

RAS also is equipped with sensors to determine orientation and detect obstacles. 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 a backup in case of laser range finder failure. A ground penetrating radar is used for crevasse detection.

4. SENSOR SELECTION

In previous chapters, various sensor modalities and their application in polar robotics was discussed. Next, the focus is on the selection of a robust suite of sensors. First, a set of criteria must be developed in order to analyze the sensor modalities to select the sensors that best fulfill the research requirements of the PRISM rover. In this chapter, a set of sensor selection criteria is defined. First, sensing requirements based on the task, the environment, and educational outreach are defined. These requirements are classified into specific criteria that must be met.

4.1 Sensing Requirements

Prior to selecting the suite of sensors to integrate with the PRISM rover, it is first necessary to determine the rover's sensing requirements. The requirements are divided into three categories: task requirements, environmental requirements, and outreach requirements. Here, we define specific requirements necessary to support the PRISM project's mission.

4.1.1 Task Requirements

The PRISM rover's mission is to complete the scientific requirements of the PRISM project. As the rover collects the radar data, it must also log the precise position at which each measurement is taken. The PRISM radar group has determined that the measurements must be made at centimeter-level accuracy (5 cm x and y, and 10 cm z). In addition to position information, video would also be useful during periods of remote operations.

4.1.2 Environmental Requirements

The rover is required to function in a polar environment. Several environmental requirements must be addressed. The rover 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 artificially or naturally occurring obstacles, e.g., sastrugies or crevasses [7, 13].

4.1.3 Outreach Requirements

Educational outreach is an important aspect of the PRISM project. To support students and educators at the kindergarten through the 12th grade level, a website has been established [61]. During field experiments, this site provides live data and video from the rover while operating in the field. It is important that the suite of sensors provides data that would be of value to students and educators [11].

4.2 Criteria for Selection

Before discussing which sensors were selected for the PRISM rover, it is first necessary to discuss the overall criteria that were used to evaluate each sensor. In particular, these are: cost, power consumption, ruggedness, accuracy, size/weight, complexity, software interface, connectivity, physical attachment, and reliability. We will discuss our requirements for each of the criteria below.

4.2.1 Cost

We choose to focus our attention on commercial off-the-shelf sensors in order to reduce cost. The cost of a selected sensor should reflect its overall necessity.

4.2.2 Power Consumption

Often, the output of a generator is proportional to its size and weight in addition to their own fuel consumption. Since the generator consumes both space and payload, sensors must be selected with minimal power consumption requirements.

4.2.3 Ruggedness

Sensors operating on the outside of the rover's enclosure must be capable of both operation and being stored 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 of up to 160 kilometers-per-hour.

4.2.4 Accuracy

Several sensors also have specific accuracy requirements. Based on the specifications from the PRISM radar group, the GPS equipment must provide a relative accuracy of within five centimeters in the x and y directions, and 10 centimeters in the z direction.

4.2.5 Size/Weight

The rover has approximately 75 kilograms of payload available for all the sensing equipment. Internal sensors must share space with the radar equipment. The space available to sensors is of the dimensions 75 x 60 x 90 centimeters.

4.2.6 Complexity and Reliability

Keeping complexity at a minimum helps insure the reliability of the overall system. With fewer components or moving parts, a sensor is less likely to have a minor failure turn into a much larger scale problem.

4.2.7 Software Interface

Java has been the primary programming language used for the PRISM rover in order to ensure the portability of implementation. It is desirable to select a sensor that utilizes an open data transfer format. We may have to write our own software to interface with the sensor rather than use an operating specific interface provided by the manufacturer.

4.2.8 Physical Mounting

The sensor must be mountable such that it may operate on a moving vehicle. Vibration will likely produce strain on the mounting of the sensors within the suite. Therefore, external sensors must be analyzed to determine if it can be mounted reliably to the exterior of the rover such that it does not vibrate loose or move out of place while the vehicle is in motion.

4.2.9 Connectivity

The sensor must be capable of easily interfacing with traditional computing hardware. Such interfaces include, but are not limited to: RS-232, USB, PCMCIA, and Ethernet.

5. ANALYSIS OF SENSOR SUITE

Given the sensor selection requirements and specification criteria discussed in the previous chapter, a suite of sensors has been selected for the PRISM mobile robot. In this section, each of these sensors is described, along with its specifications and the rational for choosing it. is discussed.

5.1 Topcon Legacy-E GPS System

The Topcon Legacy-E RTK GPS system was selected to support the rover's scientific objectives as well as its navigation and localization. These high-end GPS receivers are dual-frequency GPS+GLONASS Real-time Kinematic. The system is composed of a fixed base station and a mobile rover system.

The base station (shown in Figure 5.1) includes the following components:

- Topcon Legacy-E GPS Receiver (base configured).
- Topcon Legant GPS Antenna.
- Pacific Crest Positioning Data Link (PDL) base radio transmitter and antenna.
- Tripod.
- Cables and accessories.

The rover-based GPS system includes:

- Topcon Legacy-E GPS Receiver (rover configured).
- Topcon Legant GPS Antenna.
- Pacific Crest PDL rover radio receiver and antenna.
- Antenna pole with bipod.

Figure 5.1: Topcon GPS base station.

- Cables and accessories.

The Topcon Legacy-E RTK GPS System [63] was selected because of its versatility, ruggedness, and accuracy. The Legacy-E is much more expensive than a conventional GPS system. As accuracy increases, the equipment costs increase exponentially. One of the task requirements of the rover is to provide centimeter-level position accuracy. This unit exceeds this level of accuracy to millimeter-level relative position accuracy. Table 5.1 shows the specifications of this GPS unit [45, 63].

Since satellite visibility is a key concern when operating GPS equipment in polar regions, the Legacy-E is equipped to receive both L1 and L2 signals

Item	Value
Power	35 Watts (base system) 3.3 Watts (roving system)
Ruggedness	-40°C to 55°C Operating (receiver and Legant) -30°C to 60°C Operating (base radio) -20°C to 85°C Operating (rover radio) Waterproof No parts susceptible to vibration
Accuracy	10mm + 1.5ppm Horizontal (Global) 15mm + 1.5ppm Vertical (Global)
Size	24.0 x 11.0 x 3.50 cm (l x w x h) (receiver) 15.8 x 7.0 x 16.7 cm (l x w x h) (base radio) 21.0 x 6.1 cm (h x d) (rover radio) 6.22 x 24.3 cm (h x d) (Legant)
Weight	0.6 kg (receiver) 1.34 kg (base radio) 0.34 kg (rover radio) 1.0 kg (Legant)
Output	RS-232

Table 5.1: Topcon Legacy-E and PDL Data Link specifications.

from American GPS satellites which virtually increases the number of satellites by 1.5. This unit also utilizes Russian GLONASS satellite signals. Determining the average number of visible satellites over a 24 hour period in Greenland was tested during the 2003 field season, and discussed in later sections.

Based on the specifications in Table 5.1, this receiver meets all of the selection requirements for the PRISM rover. All components are capable of operating within their respective operating environments. The electronics of the unit are not susceptible to vibration since the equipment is entirely solid-state. However, care must be taken regarding the cables that connect the equipment because they can be easily damaged and could vibrate loose over time. The GPS rover equipment is compact and is easy to integrate into rack-mountable cases as discussed later.

The specified accuracy of the system is also exceptional. Each accuracy measure is associated with a certain error for each part-per-million (ppm). This is more easily understood as the error in millimeters for each kilometer that the rover is away from the base station. A Topcon dealer indicated that actually using the receiver, the average absolute error was at worst 10cm x,y and 20cm z [36]. Relative positioning accuracy based on specifications is unknown and must be measured through experimentation. Such experiments will be discussed and the performance shown in future chapters.

5.2 SICK LMS221 Laser Range Finder

The LMS221 laser range finder from Sick AG shown in Figure 5.2 was selected to detect obstacles for the PRISM rover. The LMS sensors has a reputation in the mobile robotics community. Carnegie Mellon University's Nomad rover utilized an LMS sensor in Antarctica [40]. Autonomous Solutions, Inc. includes the LMS221 for some of its commercial robot systems and its mobile rover for the DARPA Grand Challenge [14].

Figure 5.2: Sick LMS 221 laser range finder.

The LMS221's scanning laser produces a 180° window with a angular resolution of 0.5°. The sensor has a range of up to 80 meters depending in its configuration. This unit is also equipped with an internal heater for operating in temperatures below 0°C. Table 5.2 lists the specifications of the unit [54].

Item	**Value**
Power	20 Watts (heater off) 160 Watts (heater on)
Ruggedness	-30°C to 50°C Operating Two-hour warm-up required for operation below 0° Anti-Fog filter
Accuracy	5 cm (range up to 80 meters)
Field-of-Vision	180°
Scanning Resolution	0.5°
Size	35 x 24 x 26 cm (l x w x h)
Weight	9.0 kg
Output	RS-232

Table 5.2: Sick LMS221 specifications.

This model was selected because it is designed to operate in cold outdoor environments. Features such as an on-board heater, fog correction, and an external sun-shroud improve the survivability of the sensor. The ruggedness and accuracy of the LMS221 is also beneficial. The sensor can be stored at temperatures as low as -30°C. The sensor will operate at such temperatures after heating itself to 0° C. The sensor's accuracy is typically 5 cm with a range of up to 80 meters. The cost of the LMS 221 was reasonable in comparison to its alternatives.

The LMS221 was also selected for the PRISM rover because of its overall simplicity and few computational requirements. Sonar would require multiple transducers and micro-controllers 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 [54, 55].

5.3 BEI Technologies MotionPak II Gyroscope

The BEI MotionPak II, as shown in Figure 5.3 [9], was selected to provide heading information while the rover is turning as well as monitor its acceleration. The MotionPak II acts as two sensors in one. As a three-axis gyroscope, it provides the angular rate of rotation in degrees-per-second along the x,y and z axes. Accelerometers provide the rate of acceleration along each axis [8].

As a gyroscope, it provides the angular rate of motion in degrees-per-second along each axis. The sensor also measures acceleration forces in g's along each axis [8].

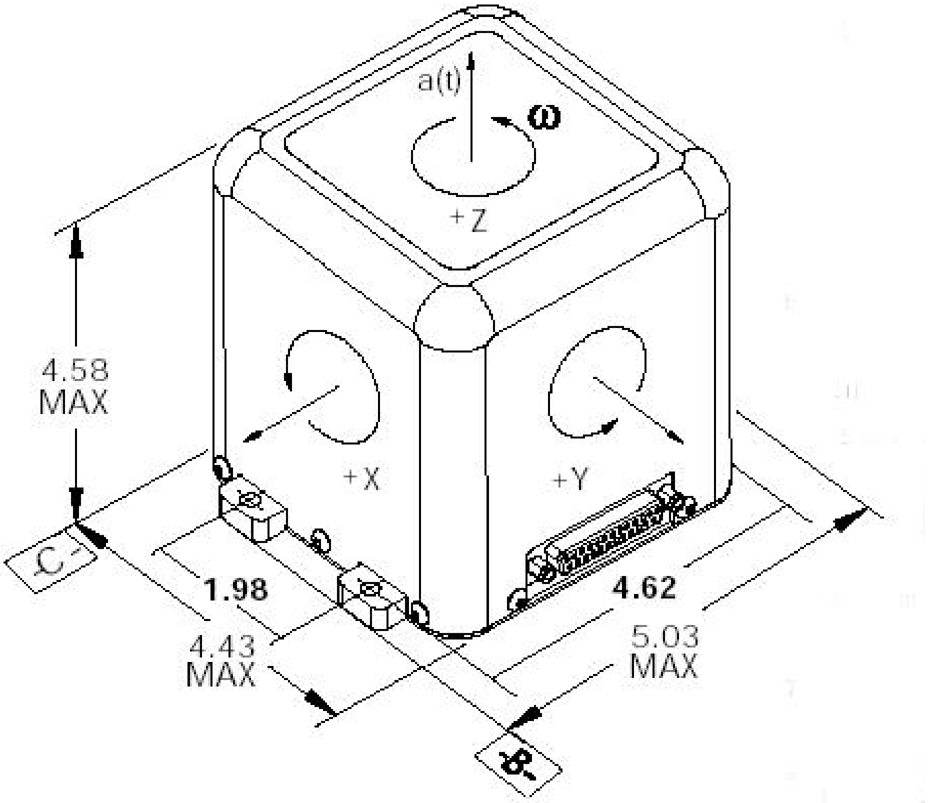


Figure 5.3: MotionPak II gyroscope/accelerometer.

While the rover is moving forward or making slight heading changes toward a target, the on-board GPS system can precisely determine the rover's heading. However, while the rover turns, the Topcon GPS system cannot accurately calculate the heading. Rather than invest in a second GPS unit, the MotionPak II becomes a convenient, low cost, alternative. By integrating the angular rate versus time, the heading is determined.

Bump and stall sensors can add greater complexity to a robotic system. By utilizing the MotionPak II's accelerometer, we no longer need such sensors. If the rover is attempting to move forward, but acceleration remains at zero, the rover is likely stuck, or its engine has stalled. While the rover is in motion, a sudden change in acceleration could indicate that the rover has encountered an obstacle or a drop-off.

Item	**Value**
Power	2 Watts (max)
Ruggedness	-40 to 85°C (operating) 4 g RMS (vibration) solid-state
Accuracy	5.0°/s (rate bias error) 125 mg (accelerometer bias error)
Size	5.03 x 4.43 x 4.58 cm (l x w h)
Weight	1.26 kg
Output	RS-232

Table 5.3: BEI MotionPak II specifications.

The MotionPak II's specifications are presented in Table 5.3 [8]. An error of 5 degrees per second seems high, however, for our purposes the accuracy is sufficient. Since the rover's heading will be determined using this sensor only, while turning in place, which often takes less than two seconds, the error from the turn will be negligible. Using the GPS, the rover recovers its path with only slight corrections. The sensor's performance, drift over time, and the effects of vibration are measured and presented later in this thesis.

Since the sensor is solid-state, it is a fairly rugged piece of equipment.

The operating temperature range for the MotionPak II exceeds the minimum requirements. The unit does not consume much of the rover's resources. It must occupy prime space since it must be centrally located. Since its foot print is small, this is not an issue.

5.4 Precise Navigation Inc. TCM2-50

The TCM2-50 shown in Figure 5.4 [47] from Precise Navigation Inc. has several roles on the PRISM rover. This particular sensor integrates a two-axis tilt sensor, a compass, and a temperature sensor. However, for our purposes, we only utilize the tilt and temperature features. Due to electromagnetic interference from the robot's engines and actuation system, the sensor may not accurately produce magnetic or compass measurements. The compass is also less effective when operated in close proximity the magnetic poles such as in the Arctic or Antarctic. By integrating several sensors onto a single evaluation board with an RS-232 interface, the overall complexity of this system is greatly reduced [49].

The primary motivations for selecting this sensor is redundancy. Unlike the MotionPak II, the TCM2-50 is capable of determining roll and pitch without knowledge of previous state. It is utilized to calibrate the MotionPak II periodically in order to remove that sensor's accumulated drift. The on-board temperature sensor is utilized to monitor the temperature within the rover's enclosure.

The sensor's specifications are presented in Table 5.4 [49]. Its ruggedness is sufficient for operating in Greenland. Vibration may have a negative impact on the accuracy of the sensor because the sensor utilizes an electrolytic fluid. If experiments show that the fluid lacks the proper viscosity, we could acquire a replacement inclinometer with a more viscous internal fluid. Vibration experiments are discussed in detail in later sections.

The inclinometer's accuracy is sufficient to determine whether the robot is

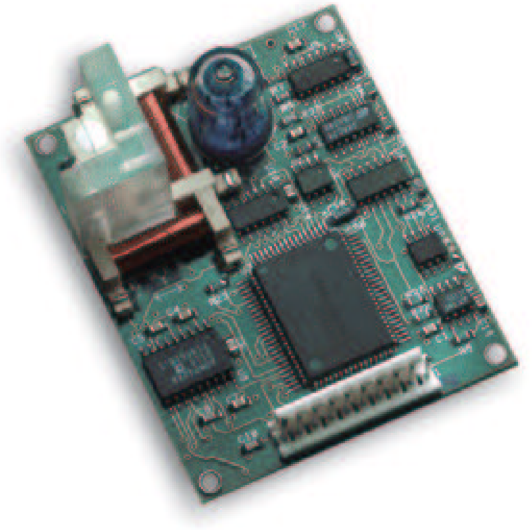


Figure 5.4: TCM2-50 orientation sensor.

Item	**Value**
Power	0.3 Watts
Ruggedness	-20°C to 70°C Operating
Accuracy	0.4° (tilt) 1°C (temperature)
Size	6.35 x 4.58 x 3.18 cm (l x w h)
Weight	0.045 kg
Output	RS-232

Table 5.4: PNI TCM2-50 specifications.

at risk of rolling. The temperature sensor's accuracy is also sufficient to determine whether the equipment is operating within a safe temperature range. The sensor does not utilize much of the rover's resources (power or space).

5.5 Rainwise WS-2000 Weather Station

The Rainwise WS-2000 shown in Figure 5.5 has been selected to provide current weather data for outreach and remote observation support. This unit integrates multiple climate sensors into a single unit. It is capable of monitoring temperature, wind speed, wind direction, wind chill, humidity, and barometric pressure [51].

Figure 5.5: Rainwise WS-2000 weather station.

As a single unit, the WS-2000 greatly reduces the cost and complexity required to monitor the weather. The unit acquired for the rover received several additional modifications to improve reliability. Since the sun is often low on the horizon in polar regions, the external solar panel was replaced by a standard power jack. The unit's wireless data output is disabled so that it would not interfere with other communication systems on the rover.

Item	**Value**
Ruggedness	-54° to 74° c (operating) 240 KPH (wind speed)
Accuracy	5 KPH (wind speed) 0.5° C (temperature) 1.0° C (wind chill) 2% (relative humidity) 1.69 millibars (barometric pressure)
Output	RS-232

Table 5.5: Rainwise WS-2000 specifications.

The weather station can obviously withstand a wide range of temperatures and wind speeds. The unit's specifications are presented in Table 5.5 [51]. While the unit's ruggedness is insured, the physical installation requires additional attention. In order to survive a strong wind storm, the sensor must be properly anchored. The external mounting of the weather station is discussed in later sections

The weather station consumes very little of the robots resources. Since the external sensors are mounted on a mast which is attached to the rover's outer frame, the WS-2000 only requires enough space inside the vehicle to house its power supply and RS-232 communication link. The unit also requires very little power.

5.6 Pelco Esprit Pan-Tilt-Zoom Camera

A Pelco Esprit camera system, shown in Figure 5.6 [46], was chosen as the vision system for the PRISM rover. The camera with 16 times optical zoom is located within a pressurized environmental enclosure. The closure is mounted on top of a pan-tilt unit which provides 360° pan and +33° to -83° tilt. In Table 5.6 [46], the Esprit's technical specifications are presented.

Figure 5.6: Pelco Esprit.

A major advantage of the Pelco Esprit is its ruggedness. The temperature operating range exceeds the minimum requirements of the PRISM project. The unit is capable of continuing its pan-tilt functions at wind speeds of up to 144 kilometers per hour and can survive at winds up to 208 kilometers per hour. The unit is capable of providing clear operation given many weather conditions. It is equipped with an internal heater, a defroster/defogger, a windshield wiper, and a sun shroud [46].

This sensor is ideal for both robotic and outreach purposes. As an outreach sensor, the camera can be used to provide live video and 360° panoramic views of the rover's surroundings. As a robotic sensor, the unit is ideal for supervisory control since a remote user could pan-tilt to view any hazards detected by the avoidance system. In future work, the camera may be integrated with the laser range finder to provide more robust obstacle avoidance.

In order to access the Pelco Esprit remotely, an Axis 2400 video server was

Item	**Value**
Power	70 Watts (max)
Ruggedness	-45 to 60°C De-ice within two hours 144 kph wind speeds (wind speed))
Pan Range	360°
Tilt Range	+33° to -83°
Size	33.9 x 19.7 x 44.32 cm (No Tilt)
Weight	9.5 kg
Control	RS-232
Output	NTSC Video

Table 5.6: Pelco Esprit specifications.

also used. The Axis provides a web-based interface for configuring, controlling, and monitoring the Esprit. The unit communicates via an on-board Ethernet port and supports up to four cameras [6].

5.7 Cruz-Pro TL30 Fuel Gauge

The CruzPro TL30 digital fuel gauge (shown in Figure 5.7 [15]) is not a typical in-dash fuel gauge. Unlike other gauges, it also provides RS-232 output using NMEA strings. Further, the unit can monitor the level of up to three fuel tanks [15, 16].

By operating as three gauges in one, the TL30 greatly reduces the overall complexity of monitoring the rover's fuel system. Fuel levels shall be monitored for both the vehicle and the generator. Based on signals from the fuel senders within a tank, the unit can output the fuel level of the tank in units of liters or as a percentage.

The unit's specifications are presented in Table 5.7 [15, 16]. The minimum operating temperature for the sensor is zero degrees Celsius. The internal temperature of the rover is well above this temperature. Only the unit's LCD screen will be negatively affected.

Figure 5.7: TL30 digital fuel gauge.

Item	**Value**
Power	0.6 Watts (max)
Ruggedness	0 to 50°C
Accuracy	2% of Percentage of Full
Size	6.1 x 10.4 cm (d x h)
Output	RS-232

Table 5.7: CruzPro TL30 specifications.

The TL30 consumes very little resources from the rover. Since the sensor will be mounted on the dash, it will not consume space reserved for equipment. With a maximum power consumption of 0.6 watts, the sensor's power consumption is so minimal that it will be connected directly to the MaxATV's power system and operate without the generator.

As of the 2004 Field Season, the TL30 has not be integrated with the rover. It should be operational for future field experiments.

6. SENSOR INTEGRATION

In this chapter, the integration of the sensors with the PRISM rover is discussed. The integration includes mounting, connectivity, and software.

6.1 Sensor Mounting

The mounting of the sensors an the rover requires careful placement in order to produce optimal performance. Some sensors have operating environment requirements that specify they be kept at a particular location. In this section, we discuss the mounting of external sensors and the internal sensors.

6.1.1 External Sensor Mounting

In this section, we will discuss the physical mounting of sensors that operate outside of the PRISM rover's heated enclosure. Since these sensors are exposed to the outside climate conditions, special care must be taken so that their mounting is both appropriate and secure. Figure 6.1 shows the sensor configuration during the 2004 Greenland field season.

6.1.1.1 WS-2000

The weather station was designed to be mounted on a pole so that it is elevated above any surrounding structures, making mounting quite easy. A one meter aluminum mast is attached to the vehicle such that the wind gauge sits about one meter above the rover. The poles are attached using clamps that are used for holding copper tubing. For each clamp, a piece of foam is placed between it and the pole in order to obtain a more secure on the pole.

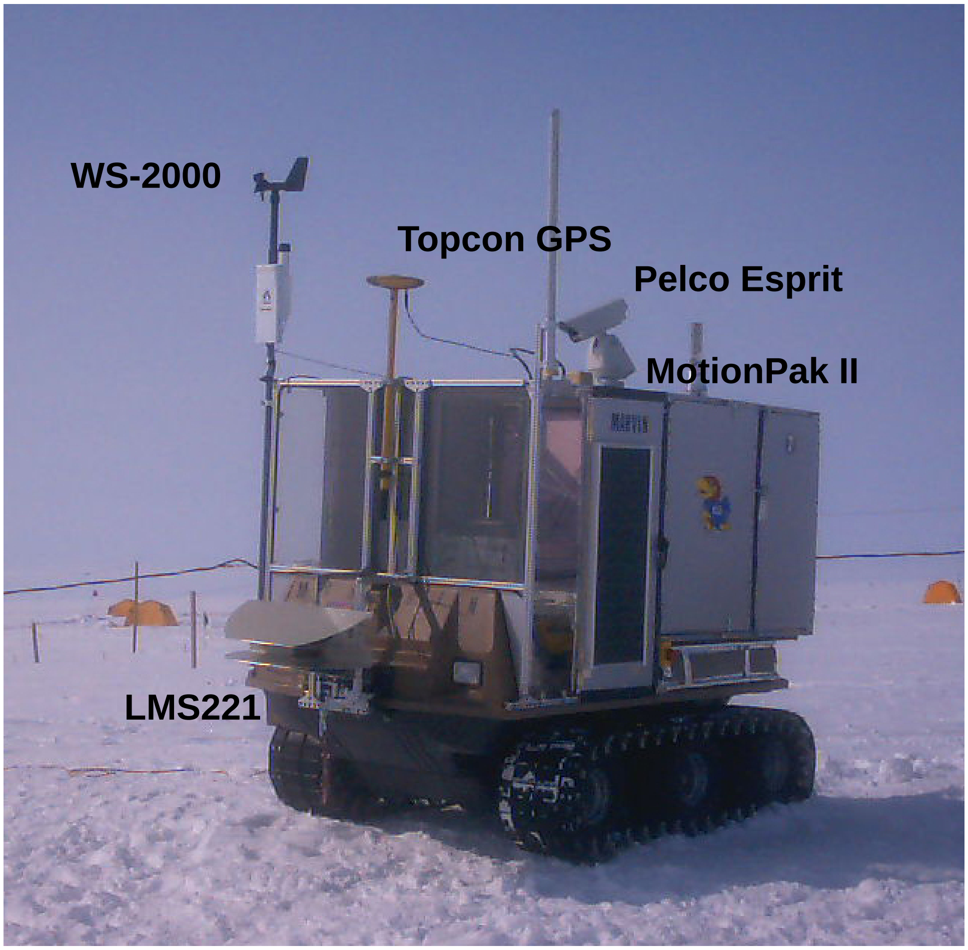


Figure 6.1: External mounting of sensors on PRISM Rover.

6.1.1.2 GPS Antennas

The Topcon GPS Receiver is composed of two components that reside outside, namely, the GPS and radio antennas. The GPS antenna is typically mounted on a one meter pole which is carried by an individual who is performing survey work. This pole is mounted on the rover just as the weather station is mounted. During future field experiments, a new mounting scheme must be devised which relocates the GPS antenna to the radar antenna being pulled by the rover.

The radio antenna is identical to a typical external cell phone antenna seen sticking out of the trunk of cars. We shall mount the antenna just as it would be mounted onto a car. The mount is bolted to the frame.

6.1.1.3 Pelco Pan/Tilt Camera

The physical installation of the pan/tilt camera is rather straight forward. We wish to view the area around the rover remotely. However, the highest priority is obtaining full visibility along its forward path. The camera is bolted to the roof near the center.

6.1.1.4 MotionPak II

The MotionPak II gyroscope is located on top of the PRISM rover near the center. It is located only a few centimeters in front of the Pelco Esprit. This location eliminates the need for performing data transformations in order to calculate roll, pitch, and yaw.

6.1.1.5 Sick LMS221

Mounting the laser range finder requires more care than mounting the other sensors. It would be ideal if a single sensor could detect both positive obstacles (sastrugi) and negative obstacles (crevasse). However, finding such a configuration has become a major challenge. As the sensor is tilted downward, the peripheral vision of the sensor becomes diminished because the sensor's scanning area becomes more skewed overlooking smaller obstacles along the sides. The scanning range is also reduced since the sensor must look somewhat downward.

Two configurations (shown in Figure 6.2) have been tested for the LMS 221. Note, in the figure, the sensor is shown in the left photograph without the sun shroud. The shroud does not affect the sensors field of view. As discussed later in this thesis, the sun shroud merely reduces error produced by the sun reflecting off of the scanning window.

Figure 6.2: LMS221 configurations.

The two configurations are as follows:

Sastrugi and Crevasse Detector: For this configuration, the sensor is placed at its maximum height (H_s), approximately 1.75 meters. The downward tilt of the sensor is 10 degrees (θ_i). Using Figure 6.3 as a reference, the estimated range of the sensor is around 10 meters before the beam would reflect off the surface. When the detector reveals a value of less than 10 meters, an obstacle may be present. Likewise, if the distance to obstacles becomes greater than 10 meters, a negative obstacle such as a crevasse or hole may lie ahead.

Sastrugi-only Detector: For this configuration, the sensor is placed at 0.5 meters with no downward tilt. In this position, the unit is capable of detecting obstacles at a range of up to 80 meters depending on the size

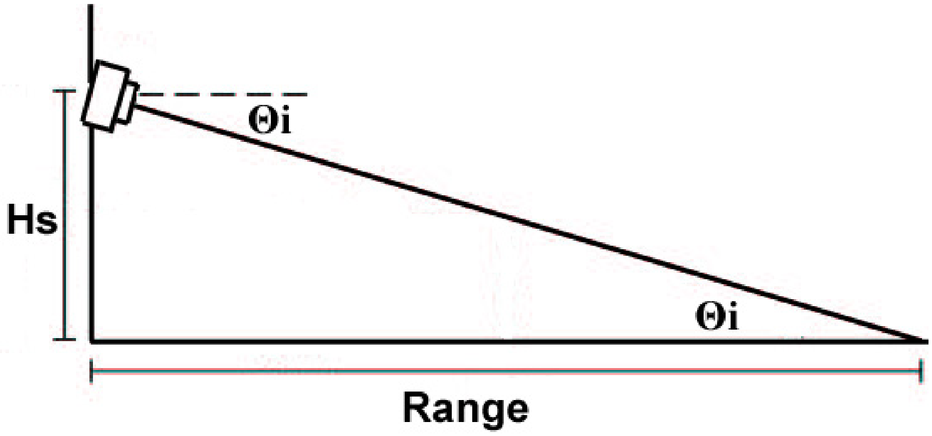


Figure 6.3: Sick LMS221 configuration.

and reflectivity of the obstacle. As the rover approaches the obstacle, the changes in range will become distinct and the range to the potential obstacle is known.

Later sections discuss testing the tilt configuration of the LMS 221 in order to determine the optimal setup. The positions will be compared to determine their performance.

6.1.2 Internal Sensor Mounting

The remaining sensors are mounted inside the rover's heated interior. While the GPS antennas were mounted externally, the receivers and radios are stored internally. Among the externally mounted sensors, each has power supplies that are stored within the enclosure as well.

During the 2003 field season, the equipment were initially strapped down to a bookshelf like structure. However, it was concluded that this resulted in a tangle of power cords, connectors, etc. For the 2004 season, many of the sensors and sensor accessories are integrated into rack-mountable cases. The sensors cases mounted within the rover is shown in figure 6.4. Each of these cases has its own power supply. In this section, we discuss each case and the sensing components that it respectively holds.

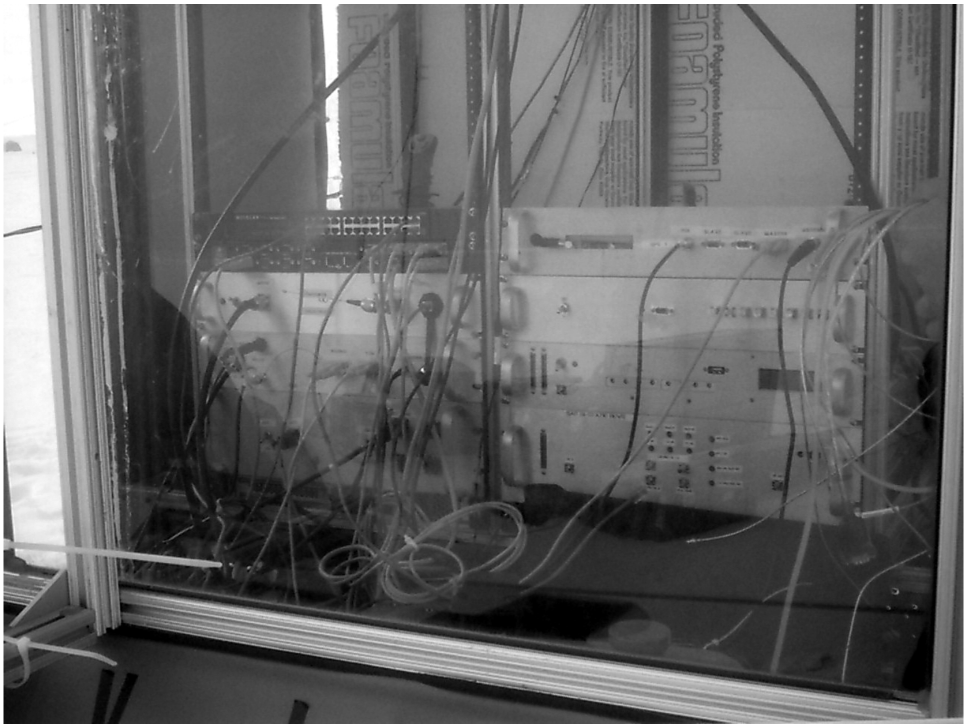


Figure 6.4: Sensor cases mounted within PRISM rover.

6.1.2.1 GPS Cases: Base and Rover

Three cases were constructed for the GPS equipment. Two of the cases were designed to hold the roving GPS receivers and their radios. The third is a non-rack-mountable case that carries the base-station receiver and radio. Figure 6.5 shows the box created for the roving receivers.

The rover cases are designed such that the user can simply connect the antennas and serial cable(s) in order to set up the GPS. Inside the case, a switch power supply provides power to both the radio and the receiver. Since the radio does not turn on once given power, the front of the case is cutout such that it can

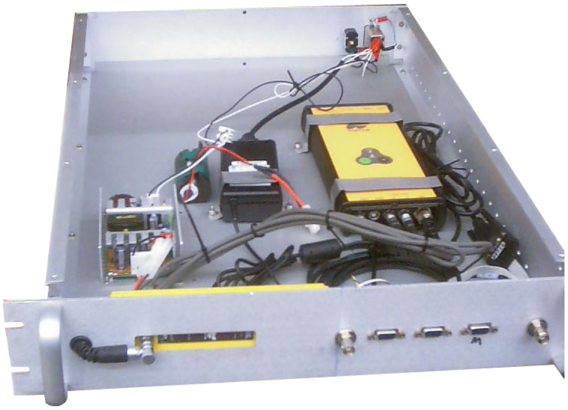


Figure 6.5: Rack-mountable case for rover GPS.

be manually turned-on. The case features one RS-232 I/O port and two RS-232 output only ports. This feature allows up to two different computers to read the data output from the GPS receiver.

The base station's case (Figure 6.6 is designed similarly except that it is built into a handled case instead of a rack-mountable case. Inside the case, a noticeable change is the power supply. Since the base station is typically powered using using a lead-acid lawn mower battery, in order to power the 35 watt radio transmitter, a 12 volt linear power supply was used. The case is built such that it is water tight.

6.1.2.2 Sensors Case

The sensors case (shown in Figure 6.7) contains only one actual sensor and components for two other sensors. The TCM2-50 is located within this case. Due to temperature requirements, it must be placed within a heated environment. This case features holes on the sides that allow the TCM to monitor the vehicle's internal temperature. The case also features the AXIS 2400 video server. To accommodate the server, a BNC input provides video to the server, an RS-232

Figure 6.6: Portable case for GPS base station.

output controls the camera, and an Ethernet jack allows the server to be connected to the Ethernet switch. Finally, the WS-2000 weather station's power supply and data logger are enclosed within the case. All three sensors and sensor components are powered using a shared 12-volt power supply.

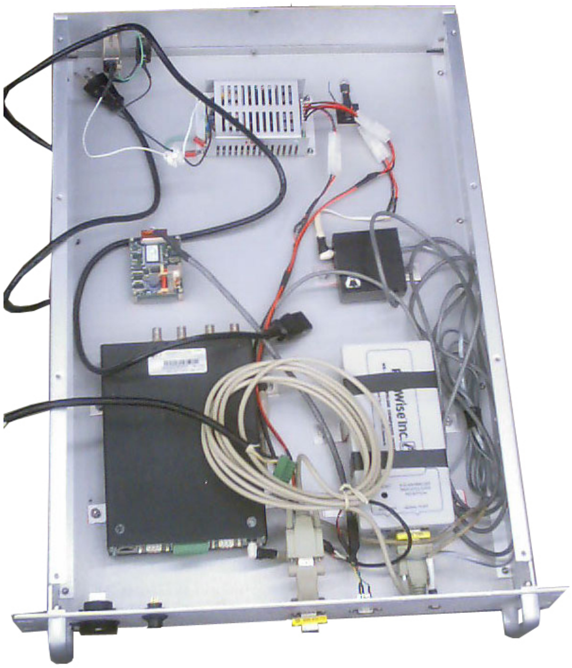


Figure 6.7: Rack-mountable case for sensors and sensor components.

6.1.2.3 Power Case

The power case (shown in Figure 6.8) contains the power supply for the Sick LMS 221. A single 110 AC input is split into four power supplies, three for the actuator and one for the LMS221. The 24-volt output from the power supply is given through the front of the case. An on/off toggle switch is used so that the LMS 221 can be turned off easily.

6.2 Sensor Connectivity

Sensor connectivity involves integrating the sensor suite with the rover's on-board computing and control equipment. Figure 6.9 shows some of the components that must be connected in order to share the sensor data. Since most computers only have a limited number of serial ports, additional hardware must be utilized to

Figure 6.8: Rack-mountable case for power supplies.

support the connectivity of multiple sensors. The sensor data gathered by the PRISM sensors are also shared with the computer systems provided by the other systems including the intelligence and radar groups. The data are also transmitted back to the tracked vehicle and/or base camp. In this section, we discuss these connectivity issues and present the hardware to facilitate the connectivity.

6.2.1 Serial RS-232 Connectivity

With the exception of the Pelco Esprit, all of the rover's on-board sensors utilize the RS-232 serial connections for input and output. A conventional PC has at most two serial ports. A hub-like device is needed to support connectivity for the sensors.

Serial connectivity is provided through the Edgeport 16-port Serial-to-USB

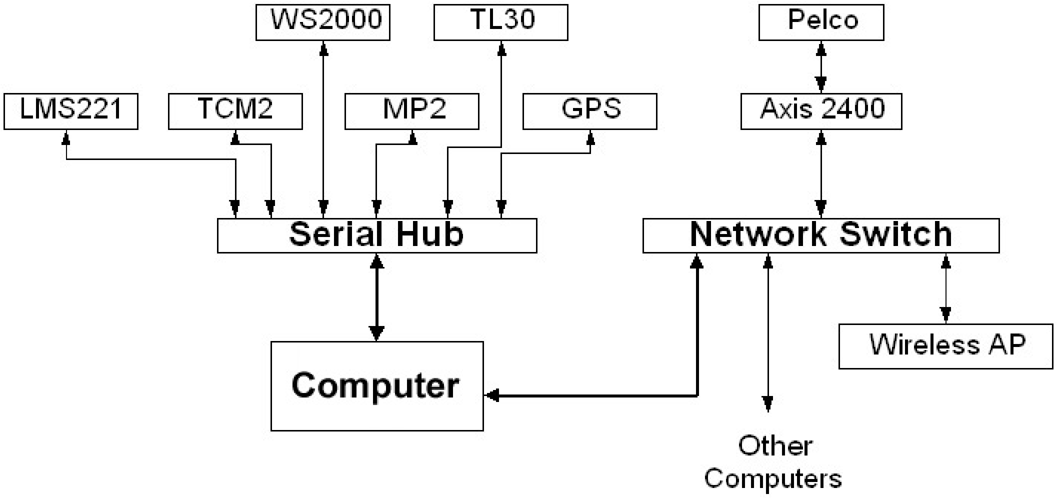


Figure 6.9: PRISM robotic sensor connectivity.

Figure 6.10: Edgeport serial hub.

Hub from Digi International (shown in Figure 6.10 [29]). The device is connected to the computer via a single USB cable. With the drivers installed, the new ports can be accessed just as on-board serial ports would be accessed. The new ports' ID numbers are in sequence with the existing ports. Since the unit is rack-mountable, it can easily be integrated with the rover's on-board rack mount system.

6.2.2 Network Connectivity

Network connectivity is necessary to link all of the computers on-board the PRISM rover. The computer systems include: the rover's main computer, the radars, and intelligent systems computer. Data is shared among these computers using the Java Remote Method Invocation (RMI) [59] interface and sockets. Network connectivity is provided through a 24-port switch from Netgear (shown in Figure 6.11 [43]).

Figure 6.11: Netgear ethernet switch.

6.2.3 Computing

The Itronix GoBook Max [30] (shown in Figure 6.12) was selected as the PRISM rover's computer. This ruggedized laptop is capable of operating at temperatures as low as -30°C and capable of surviving any shock or vibration while operating within the rover. It features a Pentium III processor [28] and currently is running the Windows XP operating system [39].

6.3 Software Integration

The software Application Program Interface (API) for the PRISM rover includes JAVA [58] interfaces for each of the sensor types: position, heading, temperature, weather, level, bump, and inertia. Instantiation of the API for sensors within the

Figure 6.12: GoBook Max ruggedized laptop.

suite is discussed. These drivers are written entirely in JAVA in order to support portability of the drivers between operating systems.

6.3.1 Overview of PRISM Sensor API

A motivation for developing the PRISM software API has been to abstract the components of the control system away from the details of the physical robot. Components such as sensors or actuators are interchanged without requiring revisions to the control system software. The PRISM sensor API is part of the overall PRISM API that defines interfaces for the abstraction of sensing components.

A set of base sensor interfaces has been defined, representing basic sensor types (temperature, position, etc.). Each interface is discussed briefly. Figure 6.13

shows the base sensor classes. The sensor event and then event listener sub-system is also presented.

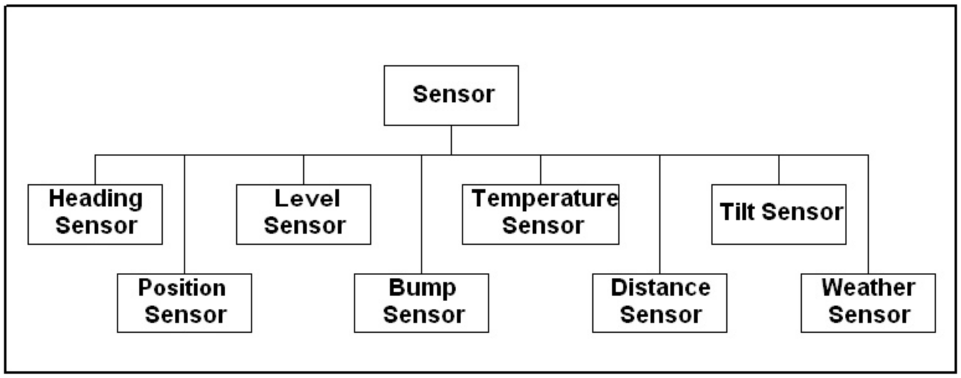


Figure 6.13: PRISM robotic sensor API flowchart.

6.3.1.1 Basic Sensor Interfaces

BumpSensor.java: The *BumpSensor* interface defines the common functions that would be associated with an array of bump sensors surrounding a robot. The function *getBumpSensorValues()* produces an array of boolean values where true indicates that it has been bumped.

DistanceSensor.java: The *DistanceSensor* interface supports sensors such as sonar or a laser range finder. Each sensor outputs values relative to its own scale (inches, centimeters, etc.). The function *getDistanceValue()* provides the raw integer measurements from the sensor. The function *getDistanceValuesInMeters()* provides the same data scaled to meters.

The properties of a single scan varies between sensors. The function *getDistanceStartAngle()* returns the heading (in radians) relative to the vehicle for which the measurements begin. The direction and angular separation (in radians) between values can be obtained with *getDistanceResolution()*. A positive resolution indicates the measurements are received clockwise.

HeadingSensor.java: The HeadingSensor interface supports sensors that provide heading values.

InertiaSensor.java: The *InertiaSensor* interface supports sensors that provide the current x, y, and z acceleration values.

LevelSensor.java: The *LevelSensor* interface supports any sensor that monitors a level such as fuel level or battery charge. The function *getLevel()* returns the current percentage of fullness.

PositionSensor.java: The *PositionSensor* interface supports sensors that determine the robot's current position. The position is represented as a two-dimensional point within a given area. The sensor can return either the x position, the y position, or the point represented by both.

TemperatureSensor.java: The *TemperatureSensor* interface supports sensors that provide temperature. Temperature is available in Fahrenheit, Celsius, or both.

WeatherSensor.java: The *WeatherSensor* interface defines functions for a weather station type sensor. Functions that are available to query are humidity, barometric pressure, wind direction, and wind speed (KPH and MPH).

6.3.1.2 Events and Event Listeners

Each of the interfaces also provides support for events and event listeners. The robot's control system only updates state values whenever it receives events from the sensors. Each sensor has its own event class, *SensorName*Event.java and a listener interface, *SensorName*Listener.java.

Events represent changes in a sensors state. The sensor events are generated at a rate which is dependent on the actual sensor. These event classes extend the *EventObject* class provided by the JAVA API.

A listener is an object that is listening for the event generated by the sensor. Listeners extend the *EventListener* class from the JAVA API. Listeners can be added or removed from each sensor's list of listeners. Whenever an event is generated, the sensor propagates the event through its list of listeners.

6.3.2 Instantiation of API for PRISM sensors

Now that the sensor API has been presented, the instantiation of the interfaces defined by the API is discussed. The drivers have been implemented entirely in JAVA. For each sensor within the PRISM sensor suite, a brief description of its implementation is described.

6.3.2.1 TopconGPSReceiver.java

This class supports the Topcon Legacy-E GPS receiver. It instantiates both the *PositionSensor* and *HeadingSensor* classes. Topcon uses a proprietary communication language known as the GPS Receiver Interface Language (GRIL) [62]. Using the Navigation Position string, the receiver can receive updated position measurements multiple times per second.

The Navigation Position string specified by GRIL provides all the information needed. The string includes: heading, position (in latitude and longitude), time of day, and the current receiver status (link quality, number of visible satellites, etc.). Upon receiving an update, appropriate heading and position events are produced and transmitted to the sensor's listeners.

While latitude and longitude are commonly used for representing location on the planet, we convert the geodetic position from latitude and longitude to UTM coordinates. For UTM, the world is divided by a grid in which each grid area is designated by a zone. The zone designations are comprised of a North/South location denoted by a letter (c through x) and the East/West is represented by a number (1 through 60). Within each grid, position is represented as Easting and

Northing. Where Easting represents East/West position and Northing likewise represents N/S within the zone. Since the rover operates in a small local area, it is unlikely to operate in more than one zone. Easting and Northing are used to represent position in x,y coordinates. This dramatically simplifies any mathematical operation related to the rover's position.

6.3.2.2 SickLaserRangeFinder.java

This class supports the SICK LMS221 laser range finder. In instantiates the *DistanceSensor* interface by providing data and events regarding the the current range to obstacles. A Datagram Specification [53] defines commands and data packets used for communication with the receiver.

Each packet contains 361 measurements indicating the distance to obstacles from 0 to 180° at a 0.5° resolution. The packet contains 722 bytes of data consisting of 361 high/low byte pairs representing that must be converted to integer values. This class provides the data as either an array the integers values representing the distance in centimeters (or millimeters, depending on the sensor's current mode), or as an array of floating point numbers representing the distance scaled to meters.

Each packet arriving from the sensor indicates the current error codes coming from the receiver. A data pollution error indicates that one of the 361 measured values is corrupt due to sensor noise. Fatal errors indicate that an error has occurred with the sensor that requires a software reset.

Since the sensor's EEPROM is configured for a given task, there is often little need for the various control commands that are defined by this class. However, several configuration commands have been implemented such that the user can reconfigure the sensor. For instance, the sensor may be configured to operate in millimeter mode. In millimeter mode, the range of the sensor is greatly diminished, but its precision increases.

6.3.2.3 Motionpak2.java

This class supports the MotionPak II gyroscope by acting as *HeadingSensor*, *TiltSensor*, *Temperature Sensor* and *InertiaSensor*. As new data is received, the values for these sensor types are updated. The new data are forwarded to each of the respective listeners through events.

The driver reads the sensor output over the serial port. Each of the MotionPak's sensors provides two bytes of data (high and low). The unit produces seven outputs: the x,y, and z angular rates, the x, y, and z acceleration, and the unit temperature [8].

6.3.2.4 TCMTiltTempSensor.java

The TCM software supports three sensors: *HeadingSensor*, *TemperatureSensor*, and *TiltSensor*. The sensor is continually polled for data. Data is transmitted from the sensor as an NMEA 0183 string [48].

6.3.2.5 WeatherStation.java

This class supports the Rainwise WS-2000. This class instantiates the *TemperatureSensor* and *WeatherSensor* interfaces. The sensor is polled twice a second to capture up-to-date weather information. The data are transmitted as a comma delimited string. Upon receiving new data, events indicating a change in temperature and weather are propagated to all listening objects [50].

6.3.2.6 TL30FuelSensor.java

This class monitors the fuel level of a single fuel tank and instantiates the *LevelSensor* interface. If the TL30 is monitoring more than one tank, an instance of this class must be created for each tank. The class is configured so that only the first instance will configure the serial communication interface. Data are communicated from the sensor using an NMEA 0183 string.

6.3.3 Sensor Fusion

Data fusion is performed for a number of reasons. A common motivation is to manipulate the data such that further information may be extracted. Another motivation is to combine redundant sensors such that a single, and more robust output becomes available.

In this section, we discuss some of the data fusion that is utilized for the PRISM rover. First, the *Position2HeadingSensor* is presented. This hybrid class is an example of how data over time is manipulated in order to provide additional information. The merging of heading information between the GPS and the gyroscope using the *MarvinHeadingSensor* is discussed. Finally, waypoint navigation is used as an example of how sensor fusion can help the rover's control system.

6.3.3.1 Position2HeadingSensor.java

By calculating the angular difference between the rover's current position and its previous position, its heading can be obtained through the use of a position sensor. While some position sensors such as the Topcon GPS receiver provide heading information already, the heading information be flawed under certain circumstances. Depending on the sensor, it may not be advantageous to re-calculate the current heading for all position updates. For example, the Topcon GPS provides a new position measurement twice every second. However, if the rover is being stationary, a new heading can be obtained even though the rover has not moved because GPS measurements provide millimeter level variation. This could result in the heading changing randomly whenever the rover pauses. When utilizing *Position2HeadingSensor*, a threshold is set such that the heading is updated only if the distance between the current and the previous positions has changed beyond a given threshold.

6.3.3.2 MarvinHeadingSensor.java

One limitation of the GPS technology is that it cannot provide an accurate heading whenever the rover is turning in place, or is sitting still. It requires a forward change in position in order to calculate the new heading. Gyroscopes provide heading information while turning in place, but suffer from drift which reduces the accuracy of the sensor whenever it is not periodically re-calibrated.

The *MarvinHeadingSensor* fuses the data from the MotionPak II gyroscope with that of the Topcon GPS receiver (as a *Position2HeadingSensor*). The *MarvinHeadingSensor* listens for update events from either sensor. However, it only forwards data update events for the sensor that is currently active. The class also listens to actuation commands from the rover's control system to determine the active sensor.

When the power to both the left and right wheels are equal, the rover is moving forward. The heading values provided by the GPS receiver are utilized. If the power between the two wheels is not equal, the rover is turning and will use the MotionPak II.

Whenever the gyroscope is not the active sensor, it is re-calibrated with the current heading values obtained from the GPS. Once it becomes active again, we are ensured that its values suffer minimally from drifting error.

This approach provides the most flexibility with the least impact on the underlying robotic control system. We could easily use the control system to directly switch between the current active sensors. However, we may on some future date rely on a different suite of heading sensors and as such, be forced to modify the underlying controller in order to use the new hardware.

6.3.3.3 Waypoint Navigation

Waypoint navigation represents the initial autonomous mode of the PRISM mobile robot. Given a set of GPS waypoints, the mobile robot must attempt to arrive at each of these points. The rover arrives at a point once it is within a set threshold distance. It will then acquire the next target point and drive toward this new point.

Waypoint navigation serves several purposes. First, if the rover is to travel over a great distance over a straight path, waypoints set milestones for which the rover must travel through. However, these milestones are not necessary. For the PRISM project, the mobile robot must follow an S-shaped pattern. This path is necessary to acquire data for the bistatic SAR.

From a sensing point of view, waypoint navigation involves the fusion of sensing with actuation. Based on the data provided by the sensors, the control system sends commands to the actuators. For basic waypoint navigation, two key pieces of information are required: heading and position. Position is measured directly from the Topcon GPS Receiver. As previously discussed, heading is available from the *MarvinHeadingSensor* class, which fuses data from the Topcon GPS Receiver and the MotionPak 2 gyroscope. Figure 6.14 presents a flowchart of the waypoint navigation system. This figure also shows how obstacle avoidance can easily be integrated with waypoint navigation to provide autonomous navigation.

By demonstrating the rover's performance during waypoint navigation, it is possible to show that the sensors used to provide these features are successfully providing the data needed for autonomous navigation.

One limitation of this approach is that obstacle avoidance using the Sick LMS 221 Laser range finder has not been integrated. This will be added and tested in preparation for the 2005 field season.

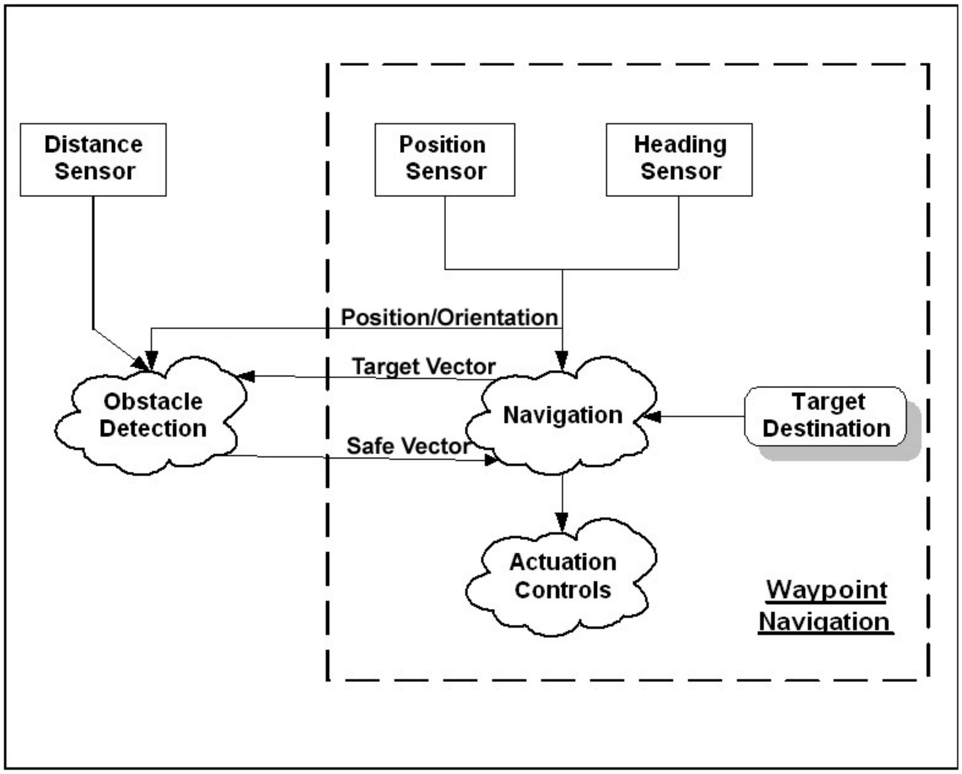


Figure 6.14: Flowchart of waypoint navigation system.

7. FIELD EXPERIMENTS

This chapter provides an overview of the field experiments performed to evaluate the PRISM rover's sensor suite. First, a set of goals for sensor evaluation is presented that will be used to direct the focus of the experiments. Next, each of the field experiments will be discussed. These experiments include: local experiments performed at the University of Kansas or surrounding region; experiments performed at North GRIP, Greenland during the summer of 2003; and experiments performed at Greenland's Summit Camp during the summer of 2004.

This chapter focuses on the objectives of these field experiments and how they relate to the PRISM sensor suite. Specific experiments will be briefly highlighted in this chapter. In later chapters, step-by-step descriptions of each experiment and the results from these experiments are presented.

7.1 Goals

For each of the experiments, we wish to address one or more of the following goals:

- Confirm the survivability and performance of the sensor while operating in a polar environment.
- Verify that the sensor meets the requirements of the PRISM researchers.
- Identify any potential weaknesses of a sensor so that it could be remedied.
- Verify proper sensor performance given its software integration with the suite of PRISM sensors.

- Verify proper sensor performance given its physical integration with the PRISM mobile robot.

Several experiments have been designed so that all of these goals may be addressed for all of the sensors within the suite. Testing was performed over two field seasons in Greenland as well as at the University of Kansas.

7.2 Greenland 2003 Field Season

During the Summer of 2003, the PRISM research team traveled to the North GRIP camp on the Greenland ice cap to perform an initial set of field experiments. These experiments focused primarily on the survivability, reliability, and feasibility of individual components. Likewise, each of the sensors was individually scrutinized. Once individual sensor tests were completed, all of the sensors were mounted onto the PRISM rover so that data could be collected as the rover drove around the camp.

For individual testing, climate survivability was the initial focus of our field experiments. Since the sensors had spent several weeks on the ice prior to our arrival, each sensor was examined to ensure that it was operating properly given the cold storage. The sensors were then tested to ensure that they could continuously operate for an extended period of time in the polar environment.

Once all of the sensors were tested for climate survivability, more sensor specific tests were performed. The GPS system was tested to determine its performance given the remote location. Since the sensor is so close to the pole, less satellites pass overhead. The satellite visibility over a 24 hour period was measured. Experiments were also performed to test the stability of the measurements near the GPS base station.

The laser range finder was tested while mounted onto the front of the rover. Since our initial goal was to have the sensor detect both traditional obstacles such as sastrugis as well as negative obstacles such as crevasses, the sensor was placed at its highest mounting position and tilted at an angle of 10°. To simulate a sastrugi, a wall of ice was constructed. To simulate a crevasse, a snow pit was likewise dug. The rover was driven toward these obstacles while the sensor was actively logging data.

Upon completion of the individual sensor tests, data collection was performed. Each sensor was mounted onto the rover. As the rover moved about, their data were actively logged. This data can now be utilized for many purposes such as simulation experiments.

7.3 Local Experiments

Between field experiments in Greenland, local field experiments were performed. Since the goal of the 2004 Greenland field experiment was to have autonomous data collection, our focus became preparing the rover for precise waypoint navigation.

Over the Spring of 2004, the rover's control system was extensively tested. As discussed previously, waypoint navigation involves the fusion of sensor data and automation control to ensure precise movement. As such, a majority of the summer experiment involved developing and testing the control system.

7.4 Greenland 2004 Field Season

During the Summer of 2004, a team of PRISM researchers returned to Greenland to perform field experiments at the Summit Camp. This year's experiments focused on the integration of technologies from each of the research groups (intelligence, communication, radar, robotics, and outreach).

The primary experiment for this field season was to verify the results obtained from the local experiments. However, the thresholds are decreased such that the traveled path will be closer to the desired waypoint path to provide greater accuracy. By demonstrating the rover's ability to follow these paths, these experiments will show that the positioning and orientation systems provide the necessary data needed to fulfill the precise navigation requirements of the PRISM project.

Since the 2003 field season, the SICK laser range finder has been remounted to a position more suitable for detecting normal obstacles, but not capable of detecting negative obstacles (discussed in future chapters). Experiments during the 2004 field seasons were performed to verify this new configuration.

Given positive results from this field experiment, the PRISM rover's sensor suite can be considered viable and the focus of research can shift toward issues of autonomy and intelligence

8. EXPERIMENTAL SETUP

In this chapter, sensor experiments are described in greater detail and independent of specific field experiments. Given the experiment, it could be performed during on or more field experiments (see Chapter 7) and/or in the robotics laboratory. For each experiment, an overview describes the motivation and goals of the experiment. The experiments vary in detail from a general task to a rigorous procedure.

The experiments involve both independent sensor tests and integrated sensor tests. Climate survivability tests involve sensor performance given the specified ruggedness criteria. GPS performance provides details regarding the systems configuration, accuracy, and reliability. Obstacle detection experiments involve the laser range finder's ability to detect positive and negative obstacles given its current configuration. Orientation measurement experiments test the performance of the MotionPak II versus the TCM2-50 given the operating environment. Finally, waypoint navigation experiments demonstrate the quality of the fused sensor data.

8.1 Climate Survivability

Above all other experiments, validating that each sensor within the suite is capable of surviving and operating within the harsh polar environment is essential. As stated previously in the requirements, external sensors must be capable of surviving wind speeds of up to 160 KPH and operating at temperatures as low as -30°C. Sensors within the vehicle must survive storage at temperatures as low as -30°C and operating at temperatures near 0°C. While each sensor has been specified to operate within these environmental conditions, it was necessary to confirm these specifications.

During the 2003 Greenland field season, each sensor was tested both individually and while integrated within the rover to ensure that it was operating correctly in the Arctic climate. Since temperatures never dropped below -20°C, additional experiments were performed using an Environtronics temperature chamber [18]. During these additional experiments, the external sensors were subjected to temperatures as low as -30°C.

8.2 GPS Performance

Verification of the performance of the Topcon GPS System is critical to determine if the system meets the stringent needs of the PRISM researchers. First, the measurement error for relative positioning must be determined. The stability of these measurements are calculated to determine the overall error bounds. Finally, the systems performance in Greenland is determined by monitoring the number of visible satellites over a 24-hour period during a field season.

8.2.1 Measurement of Relative Accuracy

In order to verify the accuracy of the GPS system, known points must be available. Relative accuracy is determined by measuring the position of each of these points. The accuracy is determined by comparing the measured distance between these points versus the known difference.

For known positions, Geodetic Benchmarks provided by the National Geodetic Survey [42, 60], a division of the National Oceanic and Atmospheric Administration [44], are utilized. These markers are embedded in the Earth's surface at known locations and represent survey points. These points can be established by several means including the use of a professional surveyor, or by using GPS technology. For this experiment, the latter has been utilized since it provides the greatest accuracy.

To determine the relative positioning error, the UTM positions of two known points is measured. On the local grid, Easting is considered the x value, northing is the y value, and elevation is the z value. The distance between the two points is calculated for each component (x,y, and z). The difference between these distances and the actual distances represent the relative positioning error in each direction. The standard deviation for measurements at each of the two points provide error bounds.

The experimental procedure is as follows:

1. Base station is established at a previously unknown location.
2. The roving receiver is placed at the first known location.
3. Data measurements are collected at this point.
4. Measurements are then collected at the second known location.
5. For each location, the average and the standard deviation for the Northing, Easting, and Elevation measurements of each point are calculated.
6. Calculate the distances between these two points.
7. Determine the error by subtracting the known distances from the measured distances.

8.2.2 Satellite Visibility

The number of visible satellites has a major impact on the performance of the RTK GPS. A minimum of four satellites must be visible to receive RTK corrections [5, 36]. The number of visible satellites may be reduced in Greenland because of its location above the Arctic Circle. Given satellite almanac data, the number of visible satellites can be predicted; however, the almanac does not take into account ionospheric effects.

Testing the satellite visibility for a typical day will provide a basic estimate of satellite performance in Greenland. These experiments, however, are incapable of showing the impact of solar activities on the GPS receiver's ability to receive satellite signals. An elevation mask is set such that satellites within 10° of the horizon are ignored since the signals from these satellites are often distorted by additional ionospheric noise [36].

The procedure is as follows:

1. Establish the base station within an open area that is free of surrounding structures and away from any major sources of RF interference.
2. Configure the elevation mask for the receiver to 10°.
3. Log the data over a 24-hour period.
4. To reduce data, for each hour, calculate the average number of GPS and GLONASS satellites.

8.2.3 GPS Measurement Stability

The following experiment was performed at the request of the PRISM radar group. The stability of GPS measurements over a 100 meter path was requested in order to build such details into the radar processing model. The relative accuracy experiment discussed earlier in this chapter is more relevant to the overall requirements of the PRISM project.

The stability of the GPS measurements indicates the error bounds for the units measurements. Stability is determined by calculating the standard deviation of measurements at fixed distances away from the base station.

The experimental procedure to determine the measurement stability is as follows:

1. Starting at one meter away from the base station, collect 20 measurements of the receiver's position.

2. Move an additional 5 meters away from the base station and collect twenty additional measurements.

3. Repeat the above procedure for up to 100 meters.

4. For each point, calculate the mean and standard deviation for Easting(x), Northing(y), and Elevation(z).

8.3 Obstacle Detection

Previously, two possible mounting configurations were presented for the Sick LMS221. The first configuration is set such that it can possibly detect both positive obstacles (sastrugi) and negative obstacles (crevasse). The second configuration only detects positive obstacles.

The motivation of testing two configurations is the belief that crevasse detection using the LMS221 may not be a viable option. Rather than immediately discount this configuration, however, we shall test the performance to determine if it works for both obstacle types. The first priority for the PRISM rover's obstacle avoidance system remains as the detection of positive obstacles.

The procedure for testing a configuration's efficiency with detecting a particular obstacle type is similar for both positive and negative obstacles. For positive obstacles, the ranging distance decreases as an obstacle is detected. For a negative obstacle, the horizon will shift backward a certain degree relative to the width of the crevasse.

The procedure is as follows:

- While logging data, the rover is driven toward the hazard.

- From the log file, determine the distances from which the obstacle is detected (if at all).
- Determine the distance from which the obstacle becomes once again undetectable (out of sensor's line of sight).
- Compare results with that of the other configurations.

8.4 Orientation Measurements

The PRISM rover is equipped with two orientation sensors, the TCM2-50 and the MotionPak II. Each sensor is thought to compliment the other. It is useful to determine the conditions for which one sensor outperforms the other.

To compare these sensors, it is necessary to determine sensor performance versus known potential weaknesses of each. First, the sensors' performance will be measured under stable operating conditions. Next, the measurement drift over time for each sensor is compared. Finally, each sensor's performance will be monitored while mounted within the vehicle to determine the affects of vibration and engine noise.

8.4.1 Drift

Rate sensors such as gyroscopes are known to possess some drift over time as a result of integrating angular rates over time and rounding errors. Rather than providing instantaneous data directly from the sensors, rate sensors provide their measurement by tracking the change in the sensor's output over time. It would be advantageous to determine the drift of the MotionPak II over a 1 minute period.

Inclinometers such as those used for the TCM2 provide tilt information instantaneously based on the current orientation of a dielectric fluid within the sensor. The TCM2 relies on a magnetometer for heading information. Neither of these sensors should produce drift. This sensor shall act as a baseline used for comparison with the rate sensor.

The experimental procedure involves placing each sensor on a level surface with only ambient vibration. Their initial measurements will be zeroed. Data from the sensor will be logged for 1 minute. After that minute, the measurements should continue to read 0° for roll, pitch, and yaw. Any measured change in these three values represents the sensor's total drift for 1 minute.

8.4.2 Vibration

For both sensors, vibration and magnetic interference from the vehicle and generator's engines could affect the sensors performance. With heavy fluctuations in rate from the vibration, the performance of the MotionPak 2 will certainly diminish when determining roll and pitch. However, for measuring heading, this sensor experience little-to-no performance loss.

In the TCM2-50's provided documentation, a warning is provided indicating that the dielectric fluid within the inclinometers may not have enough viscosity to accurately function within a highly-vibrating environment. In addition, the magnetic fields from the PRISM rover's two engines could affect heading measurements from the magnetometer. Further testing is necessary to determine the effect.

The procedure for determining the impact of vibration is similar to that of the drift. Each sensor will be placed on a level surface with only ambient vibration. Their initial measurements will be zeroed. The rover's engine will be started and the data will be logged for 1 minute. The above procedure will be repeated with both the rover's engine and the generator operating.

The results from this experiment are compared with the results from drift to determine how much the error was affected entirely by vibration.

While the rover's engine is running, the sensor's tilt values are record. These values are compared with those of the drift to determine the impact of vibration on the sensor's accuracy.

8.5 Waypoint Navigation

Prior to departure for the 2004 Greenland Field Season, waypoint navigation was tested to verify that the vehicle could properly follow a pattern similar to that required to support the bistatic SAR radar. Figure 8.1 demonstrates the path that the rover must follow. The vehicle moves in swaths in which it drives in one direction for a set distance, it then turns at a right angle and drives a different set distance, it turns at a right angle in the same direction as the previous turn, and continues the process until it has to stop.

For this experiment, the width and length were both set to 10 meters. The position of starting point was measured. Using the Easting and Northing values of the starting point, the next two points were calculated. Given these three points, the control system calculates new waypoints in real time so that the vehicle continues in the proper pattern. The results from following the path are presented in a later chapter.

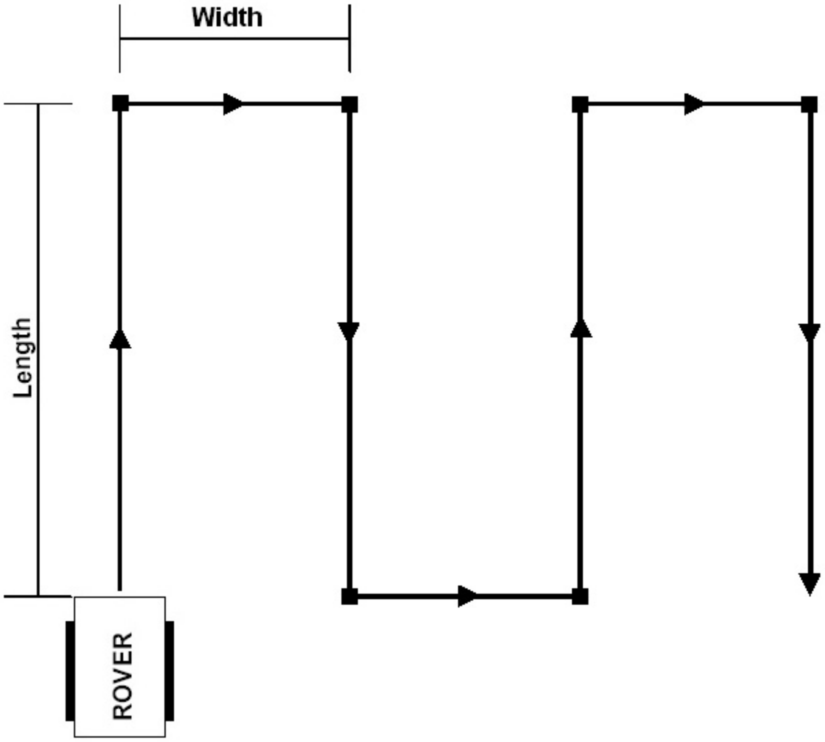


Figure 8.1: Rover's waypoint path for bistatic SAR.

9. RESULTS AND ANALYSIS

A number of experiments were defined to verify sensor performance. These experiments involve evaluation of the sensors, both qualitatively and quantitatively. The qualitative experiments determine the overall performance of a sensor given a particular setup, indicating whether on not the sensor being analyzed is viable. The quantitative experiments determine measured properties of a particular sensor that are not provided by the specifications, but are of interest to PRISM researchers.

9.1 Climate Survivability

During the Greenland field experiments of 2003 and 2004, the climate survivability of each sensor was analyzed. External sensors were also tested in a temperature chamber at the University of Kansas. In this section, we describe the performance of each sensor and discuss how issues were remedied.

Legacy-E GPS: The GPS roving and base receivers operated correctly during all field experiments. Batteries were a major issue during the 2003 field season. When operating in high-power mode (35 watts), the base station could drain a lead-acid lawn-mower battery in less than three hours. The rover radios would also lose their charge quickly as well. Batteries do not maintain their charge well in cold. For the 2004 field season, no GPS equipment operates using batteries. The base station is now powered by a Honda EU2000i generator [19].

LMS221: The LMS221 heater operated correctly and defrosted the sensor in about the same amount of time required to heat the vehicle for it to start.

The unit was capable of taking measurements of the icy surface without any difficulty. One problem did however arise, whenever the vehicle turned toward the sun, the sensor would produce either a data pollution error or a fatal error. The sensor's sun shroud was then attached and the issue was never replicated.

TCM2-50: The tilt and temperature features operated correctly. As expected, the compass was incapable of providing reliable heading information once the vehicle's generator was started. This issue is not of much concern since the sensor was never intended for to be used heading measurements.

WS-2000: The weather station had one difficulty during the 2003 field experiment. The wind-vane would fail to rotate properly and became rigid from the cold. Upon returning, the wind-vane moved freely. The problem was however replicated using the temperature chamber. The gauge was replaced prior to the 2004 field season. It has since proven reliable for collecting outreach data from the field.

Pelco Camera: During the 2004 field season, the Pelco Esprit was utilized to capture video for the PRISM outreach team. The unit was capable of providing full pan and tilt around the rover's surroundings. The heated and pressurized enclosure was capable of keeping it fog and frost free.

MotionPak II: The MotionPak II was acquired prior to the 2004 field season and tested then. The sensor operated correctly throughout the field season. Its mounting on the rover's roof remained stable and resulted in no complications.

TL30: The TL30 fuel gauge has not yet been analyzed. This sensor was acquired too late prior to the 2004 field season for it to be safely integrated into the rover's fuel systems.

From the results above, it is concluded that the PRISM sensor suite is rugged enough to handle the environmental requirements necessary. With the exception of the TL30, each sensor was analyzed and if an unexpected flaw occurred, it was addressed and tested during future field experiments

9.2 GPS

In this section, the results from the experiments discussed in the previous chapter are presented.

9.2.1 Relative Accuracy

Two known reference points were selected. Their known positions (shown in Table 9.1) were obtained from the National Geodetic Survey.

	Northing	**Easting**	**Elevation**
Position 1	4319196.888	306619.865	217.010
Position 2	4316143.825	302558.990	-54.360

Table 9.1: Topcon GPS: known UTM position (in meters).

At each point, GPS measurements were collected for one minute. From these measurements, the average and standard deviation for Northing, Easting, and Elevation were calculated (see Table 9.2).

	Northing	**Easting**	**Elevation**
Avg. Position. 1	4319199.145	306619.030	214.043
Std. Dev Position. 1	0.003	0.003	0.016
Avg. Position. 2	4316146.092	302558.149	268.381
Std. Dev Position. 2	0.007	0.004	0.016

Table 9.2: Topcon GPS: measured UTM position (in meters).

The known distance between the two points is compared with the measured distance. The difference between these distances represent the relative positioning error (Table 9.3).

	Northing	**Easting**	**Elevation**
Actual Dist.	3053.063	4060.875	-54.360
Measured Dist.	3053.053	4060.881	-54.338
Error	0.010	0.006	0.022

Table 9.3: Topcon GPS: relative positioning error (in meters).

For Northing, Easting, and Elevation, the maximum measured standard deviation for each becomes the error bounds. The relative accuracy of the Topcon GPS receiver was measured as:

$$\mathbf{x = 0.006 \pm 0.004 \text{ meters}}$$
$$\mathbf{y = 0.010 \pm 0.007 \text{ meters}}$$
$$\mathbf{z = 0.022 \pm 0.016 \text{ meters}}$$

These results show that the relative accuracy of the Topcon GPS receiver exceeds the needs of the PRISM project as specified. The data also exhibits a common trait of GPS accuracy in which the z-axis error is often double the error of the x and y axes.

9.2.2 Visibility

The availability of satellites over a 24 hour period at North GRIP in Greenland is presented in Figure 9.1 and Table 9.4.

Throughout the day, there are always enough satellites available to meet the RTK GPS minimum of four. The number of GPS satellites was always acceptable. There was a brief dip in visibility during the overnight hours from 2am to 8am.

Satellite visibility for GLONASS is much smaller than GPS. This is to be expected since the GLONASS satellite constellation includes fewer satellites. Furthermore, the GLONASS network is focused over Russian controlled areas rather than remote regions such as the Arctic.

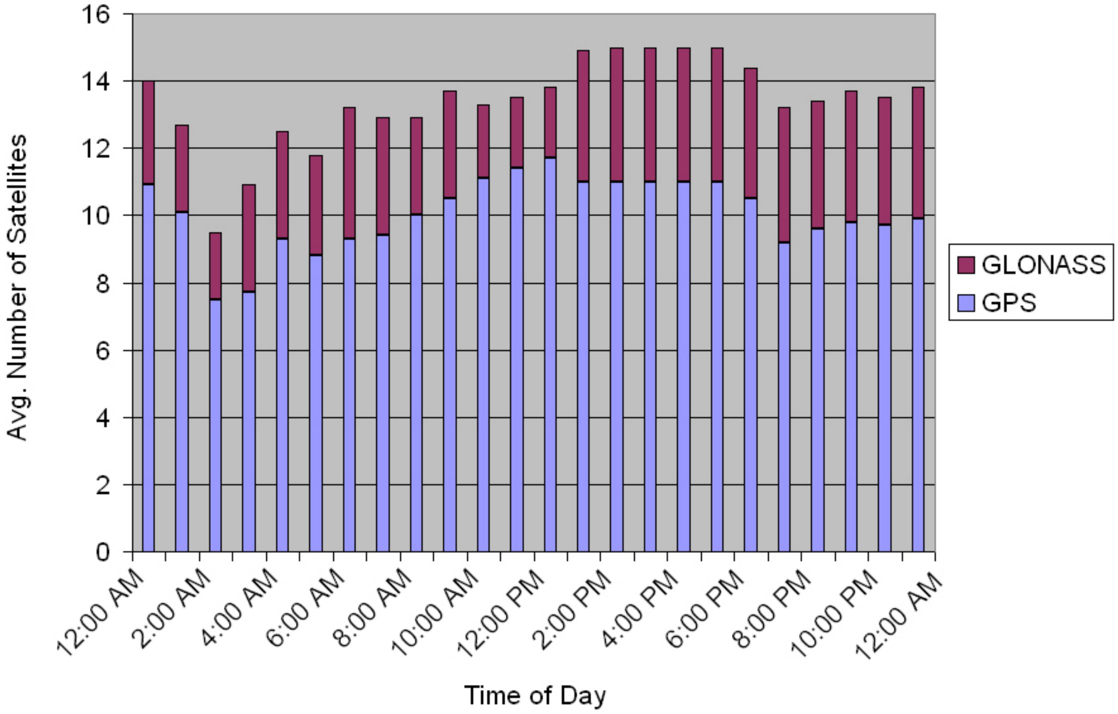


Figure 9.1: Topcon GPS: 24-hour satellite visibility.

9.2.3 Stability

In Figure 9.2, the standard deviation of GPS measurements from the Topcon GPS receiver within 100 meters of the base station are presented. These measurements and their respective standard deviations are divided into their three components: Easting, Northing, and Elevation. This chart provides a concise view of the Topcon GPS Receiver's stability near the base station.

From this data, no solid conclusions could be made regarding the effects of distance relative to the base station and the standard deviation of the measurements. Typically, it is considered that the receiver's error increases by only one part-per-million. In other words, for every kilometer that the roving receiver moves from the base station, one millimeter of error is added. As such,

Interval Start	**Interval Stop**	**Avg GPS**	**Avg GLONASS**	**Total**
12:00 AM	12:59 AM	10.9	3.1	14.0
1:00 AM	1:59 AM	10.1	2.6	12.7
2:00 AM	2:59 AM	7.5	2.0	9.5
3:00 AM	3:59 AM	7.7	3.2	10.9
4:00 AM	4:59 AM	9.3	3.2	12.5
5:00 AM	5:59 AM	8.8	3.0	11.8
6:00 AM	6:59 AM	9.3	3.9	13.3
7:00 AM	7:59 AM	9.4	3.5	12.8
8:00 AM	8:59 AM	10.0	2.9	12.9
9:00 AM	9:59 AM	10.5	3.2	13.7
10:00 AM	10:59 AM	11.1	2.2	13.3
11:00 AM	11:59 AM	11.4	2.1	13.5
12:00 PM	12:59 PM	11.7	2.1	13.8
1:00 PM	1:59 PM	11.0	3.9	14.9
2:00 PM	2:59 PM	11.0	4.0	15.0
3:00 PM	3:59 PM	11.0	4.0	15.0
4:00 PM	4:59 PM	11.0	4.0	15.0
5:00 PM	5:59 PM	11.0	4.0	15.0
6:00 PM	6:59 PM	10.5	3.9	14.5
7:00 PM	7:59 PM	9.2	4.0	13.3
8:00 PM	8:59 PM	9.6	3.8	13.4
9:00 PM	9:59 PM	9.8	3.9	13.7
10:00 PM	10:59 PM	9.7	3.8	13.5
11:00 PM	11:59 PM	9.9	3.9	13.7
	Average	10.1	3.3	13.4
	Minimum	7.5	2.0	9.5
	Maximum	11.7	4.0	15.0

Table 9.4: Topcon GPS: average satellite visibility at NGRIP.

when working within a 100 meters of the base station, no distinct change in stability will be known. The standard deviation results from the effects of the ionosphere and any local interference.

One fact that this data illustrates is the difference in stability between the vertical component (elevation) and the horizontal components (Easting and Northing). As stated previously, the vertical error is at least twice the error of the horizontal measurements. The figure shows that this property holds with respect

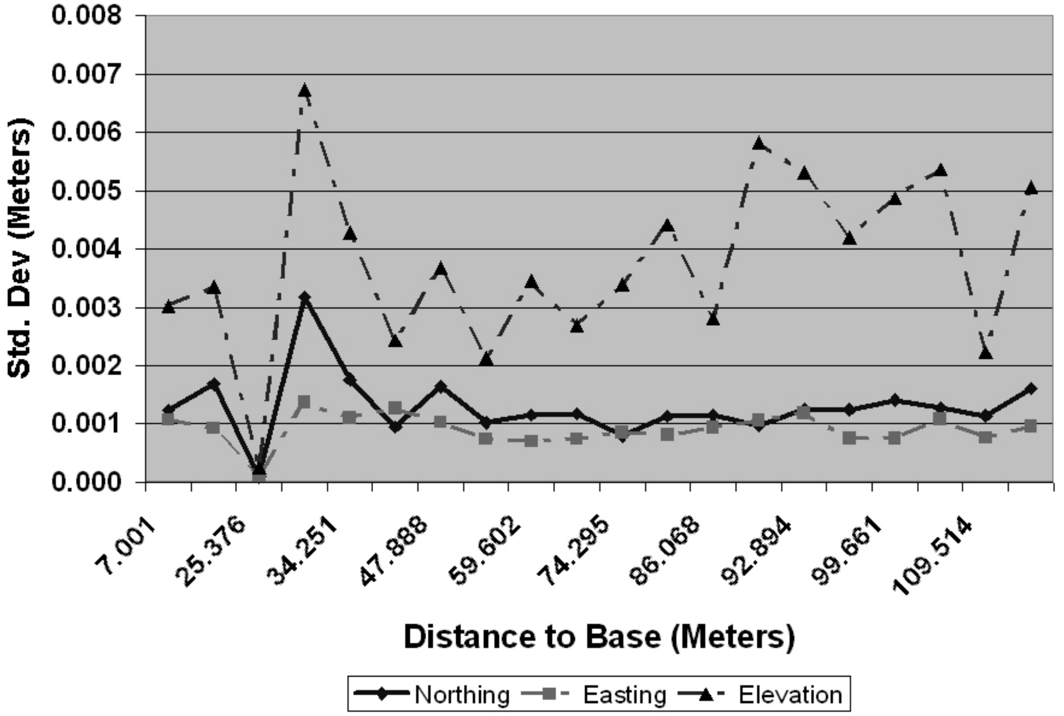


Figure 9.2: Topcon GPS: measurement standard deviation vs. distance to base

to measurement stability.

9.3 Obstacle Detection

In this section, the performance of the LMS221 is compared using the two possible mounting configurations discussed previously. First, the results will be presented in which the laser range finder is being utilized as both a positive and negative obstacle detector. Next, the performance of the sensor as a positive-only obstacle detector is presented. Finally, a brief discussion will evaluate how the two configurations compare.

9.3.1 Configuration #1: Positive and Negative Obstacle Detector

Figure 9.3 presents the results of obstacle detection for a positive obstacle. The obstacle is a man-manned igloo at the North GRIP camp. Its roof was partially collapsed, and stood only about 0.5 meters tall.

From the figure, the horizontal segment of dots shows the surface of the ice at about 8 meters in front of the vehicle. Obstacle first emerged at this distance. The figure shows the igloo to the right of the vehicle about 5 meters from the rover. With the igloo five meters to the right of the rover, and less than five meters in front of the vehicle, we were no longer capable of tracking the obstacle.

Figure 9.4 presents an image of the negative obstacle encountered by the rover and the LMS221 profile of the obstacle. The obstacle was first detected at 10 meters. From this angle of approach, such an obstacle is easy to detect since the the snow pit is relatively long and narrow. We are capable of easily differentiating the snow pit from the normal ice surface.

The LMS221 did not perform optimally when detecting a crevasse-like obstacle. When approaching the snow-pit from a different angle, the width of the pit is about 3 meters and the length is about 25 meters. As such, with this configuration, the trench was not detectable. The horizon shifted back for about half a second before it returned back to its original position. Such a shift appears almost identically to the output from the sensor whenever it hits a bump.

9.3.2 Configuration #2: Positive-only Obstacle Detector

Figure 9.5 presents the detection of a positive obstacle given the second configuration of the LMS221. In this configuration, the sensor is mounted low on the rover and level in order to detect only positive obstacles. In the figure, two distinct obstacles are seen, a snowmobile and a sledge. The two are approximately five meters apart. Each can be distinctly detected using the laser range finder. At

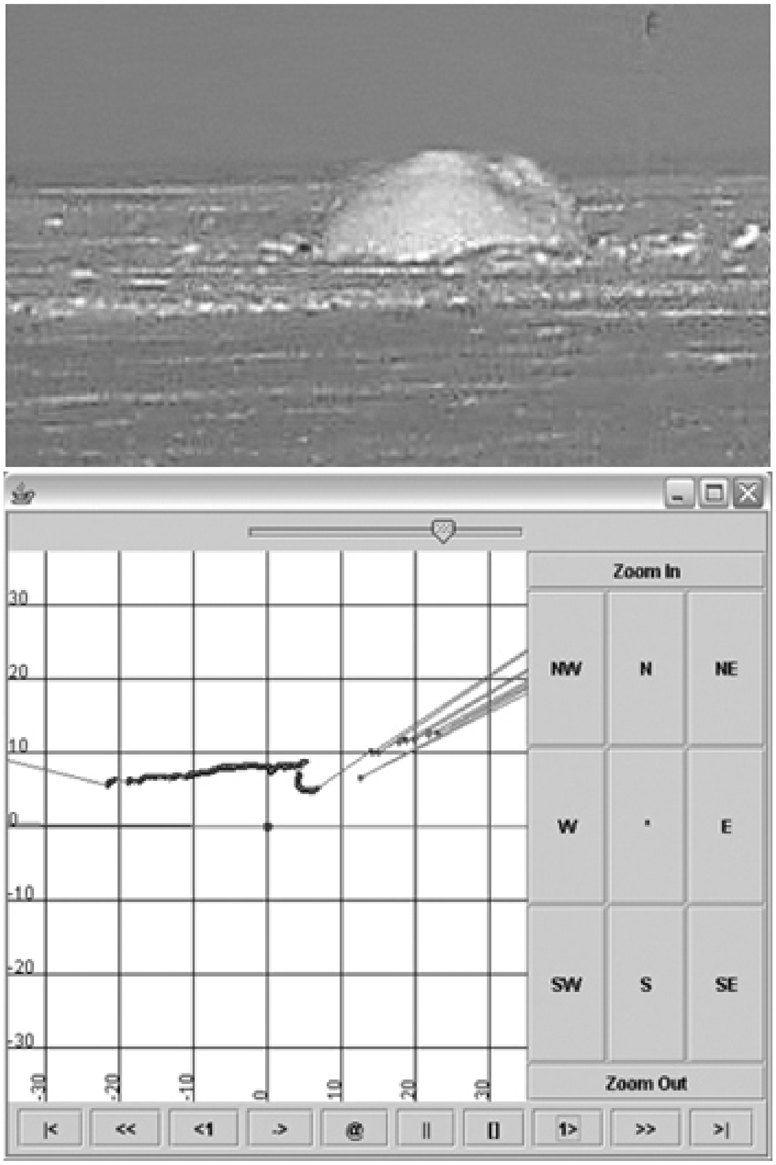


Figure 9.3: LMS221: igloo.

30 meters, they appear as just a single obstacle, but at about 20 meters, the two obstacles can be seen separately. The sledge is an example of an obstacle that is very low to the ground, but could cause serious damage to the vehicle in case of a collision

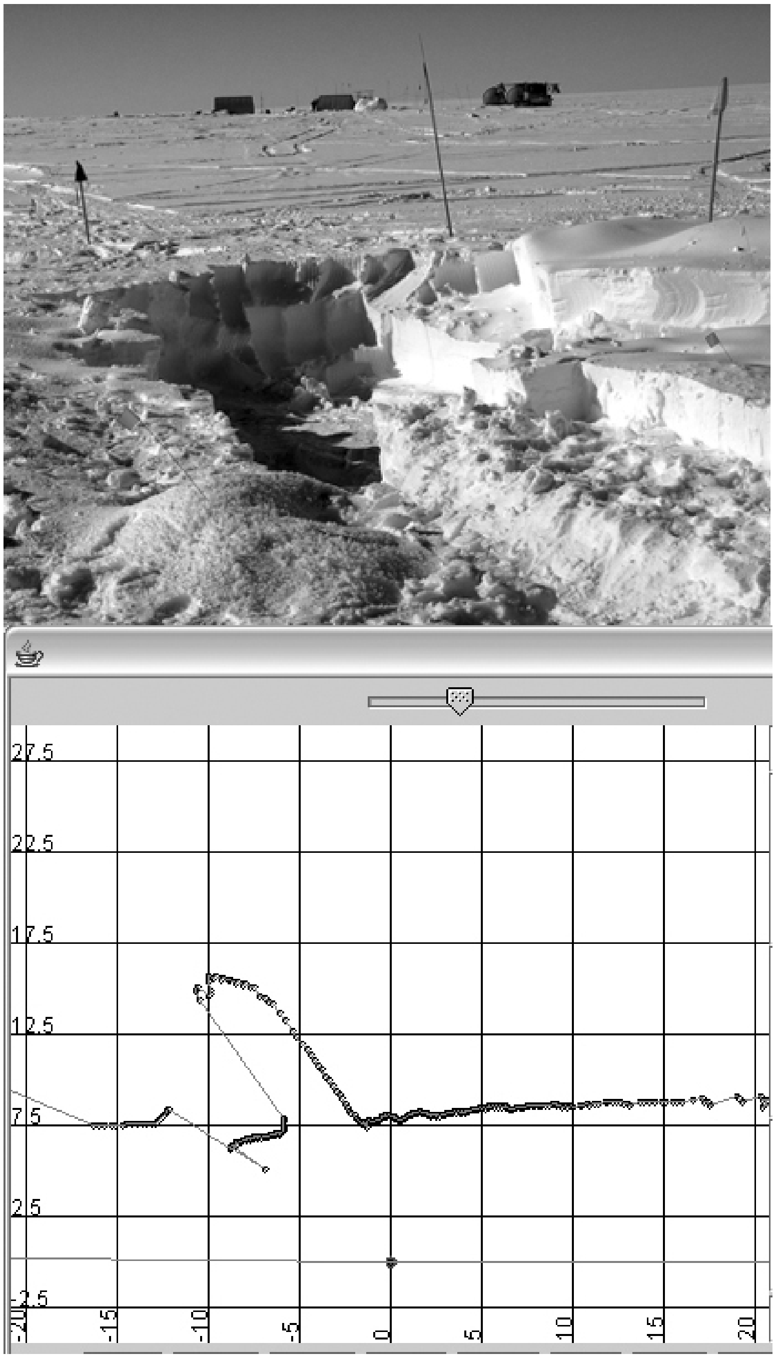


Figure 9.4: LMS221: snow pit.

It should be noted that in this section, all photos of the obstacles were taken from the left side of the vehicle pointing outward. Therefore, what appears toward the center of the photo is actually to the left of the vehicle.

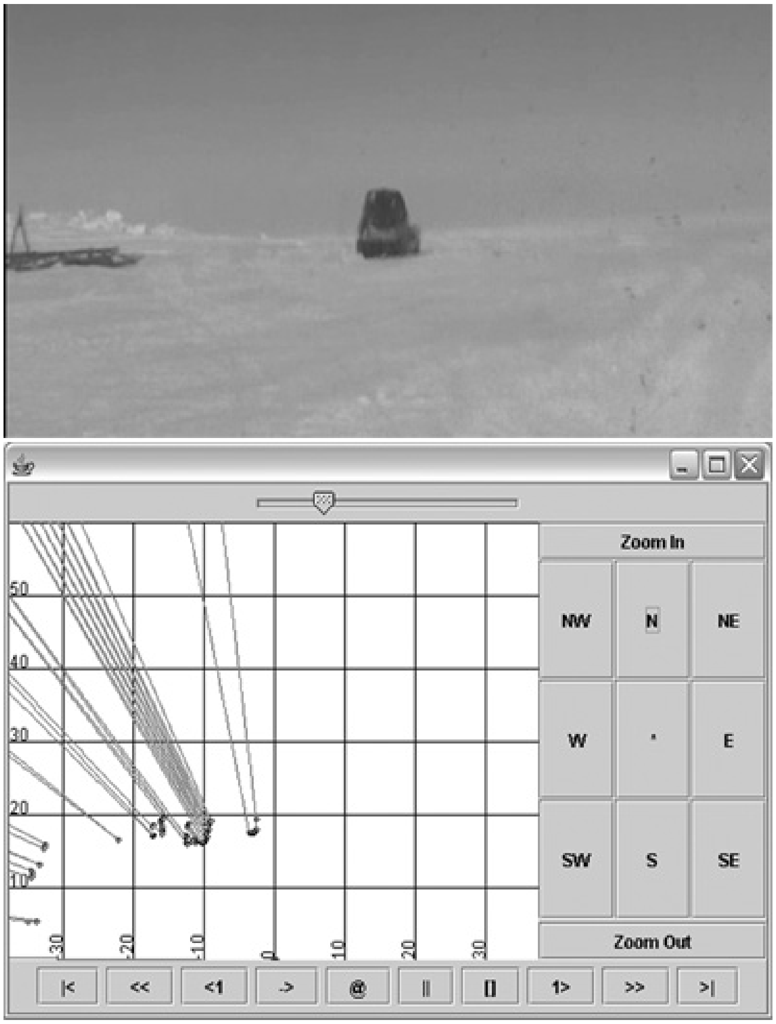


Figure 9.5: LMS221: snow mobile.

Figure 9.6 presents a photo of a sastrugi-like obstacles and the LMS221 scan image of that obstacle. This figure shows two key properties of this LMS configuration. First, the sensor can clearly detect low lying snow-based obstacles. This obstacle is less than half a meter in height. Second, at the same height, their are sastrugi surrounding the left perimeter of the rover. With the previous configuration, such obstacles would have been overlooked.

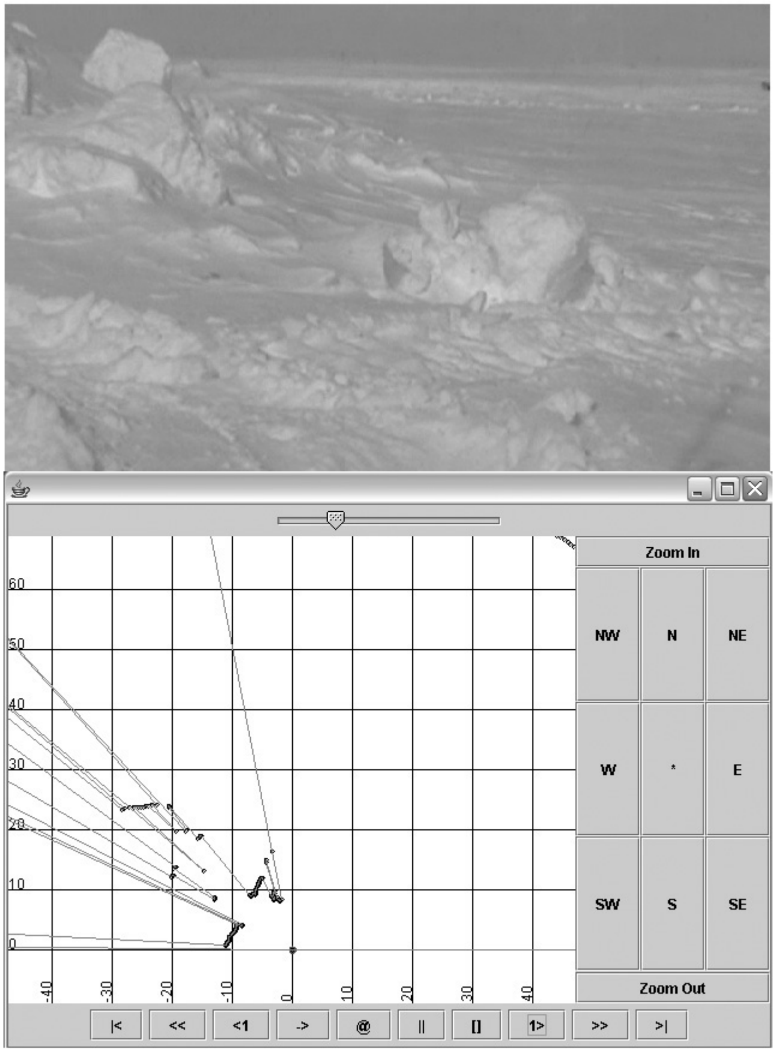


Figure 9.6: LMS221: sastrugi.

Figure 9.7 shows both a photo and LMS scan image of a series of flags with a power cable strung between them. From the image, one can not only see the flags, but also traces of the cable. The cable cannot be seen entirely, but it does cross the laser range finder's path at several points. From the LMS scan image, it is obvious that the there are obstacles to the left of the rover for which it could not pass through.

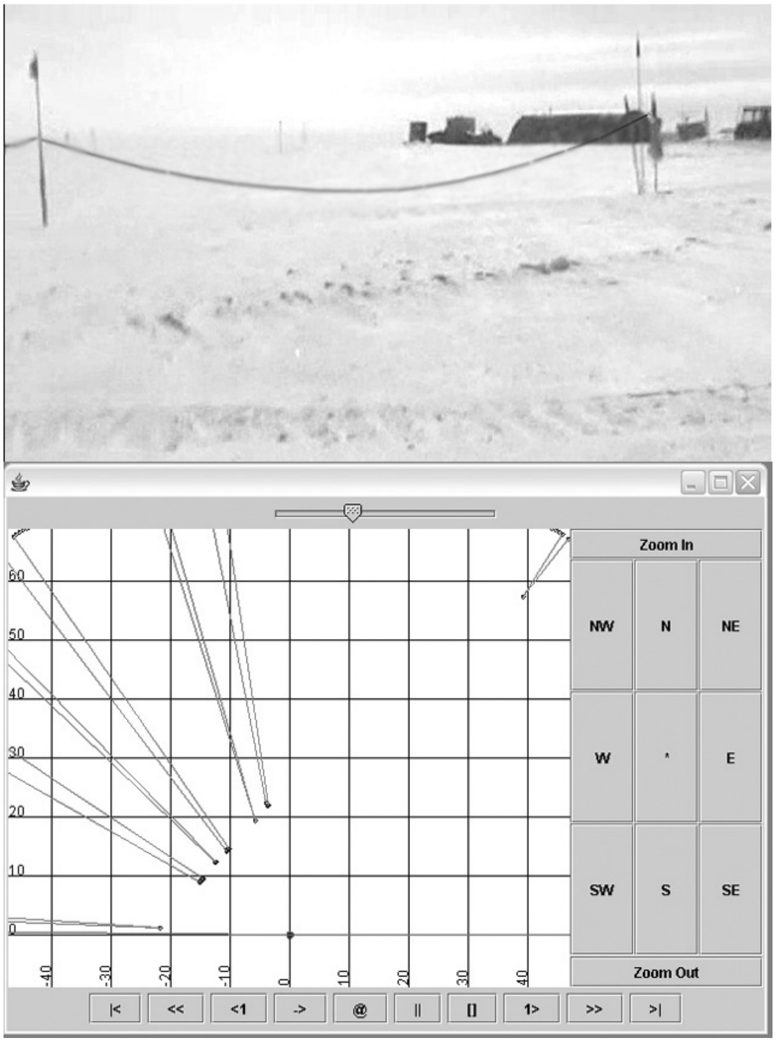


Figure 9.7: LMS221: flags and power line.

With this configuration, obstacles were often first detected at 4 meters. By 30 meters, a general estimate of the obstacle's size could be made. At less that 20 meters, the general shape of the obstacle could be determined. These properties held regardless of the obstacle's location within the sensor's field of vision. The sensor was also capable of tracking the obstacle at a distance of up to one meter for the full 180° field of view.

9.3.3 Discussion

By comparing the results of the two configurations, it is concluded that the second configuration provides more information with greater reliability. The first configuration was not reliable with detecting obstacles that are of greatest concern, crevasse. Such obstacles would appear the same as if the rover hit a bump. Therefore, the only area of comparison left for these two configurations is their ability to detect positive obstacles.

The first configuration had a distinct range. Based on the height of the sensor and the tilt, the distance until the laser would impact with the snow was known. To even detect crevasses, this range was only 10 meters at best. The peripheral vision in this configuration was also unreliable because smaller obstacles were difficult to detect to the sides of the vehicle. If the vehicle were to avoid an obstacle in front of it, it could blindly turn into an obstacle to the left or right that it had not seen in its blind spot. Finally, to actually detect an obstacle, the software would have to filter out the known horizon and detect only changes either in front of or behind this horizon. However, the horizon can itself move forward and backward depending on the tilt of the vehicle.

The second configuration had a much better performance. The sensor operated out to its maximum range of 80 meters. It often did not detect obstacles until they were within a range of 40 meters. This reduced range can be attributed to surface reflectivity and the shape of the obstacle. Once an obstacle was within this 40 meter area, it could be tracked consistently. Since the sensor was mounted low, at 0.5 meters, it was capable of detecting very small obstacles that pose a risk to the vehicle. Since an artificial horizon does not exist beyond the maximum distance of 80 meters, the software is not required to filter out any data. In addition, since the sensor is pointing outward with no tilt, it is not as sensitive to bumps and tilts.

9.4 Orientation

The experimental results for testing the effects of drift and vibration on the orientation sensors are presented below in Tables 9.5 and 9.6. For each, Trial 1 shows the sensor's drift over one minute. Trial 2 shows the effects of vibration on the sensor from the rover's engine only. Trial 3 shows the effects of vibration on the sensor from the rover and generator's engines.

Trial	Engine	Generator	Roll Error	Pitch Error	Yaw Error
1	off	off	0.026	0.036	0.106
2	on	off	0.440	0.888	0.391
3	on	on	0.555	1.120	0.649

Table 9.5: TCM: stability and response to vibration.

Trial	Engine	Generator	Roll Error	Pitch Error	Yaw Error
1	off	off	0.056	0.096	0.002
2	on	off	59.599	60.486	0.007
3	on	on	85.201	56.318	0.006

Table 9.6: MotionPak II: stability and response to vibration.

The TCM2 proved to provide the best overall stability of the two orientation sensors. The impact from vibration on roll and tilt were negligible. The TCM2-50's compass proved to be more stable than expected given the electromagnetic noise from the engine and the generator. The compass provided a fairly consistent heading regardless of electromagnetic noise. During future field operations, this sensor may be utilized as a heading sensor as well. However, for the 2004 Greenland Field System, the sensor's enclosure would make sensor calibration quite difficult. In addition, the linear actuators were not active during this experiment, which could cause further heading error.

The MotionPak II suffered from very slight drift over a one minute period when no vibration was present. Once the engines were active, the error from vibration became quite noticeable with respect to roll and pitch. Since the sensor relies on the integration of the angular rate over time, with the angular rate only fluctuating at a degree per second or less, the error accumulates over time if unfiltered. For future field experiments, a filter will be applied such that the angular measurements below a set number of degrees per second will be ignored. The yaw error for the MotionPak II remained small regardless of vibration.

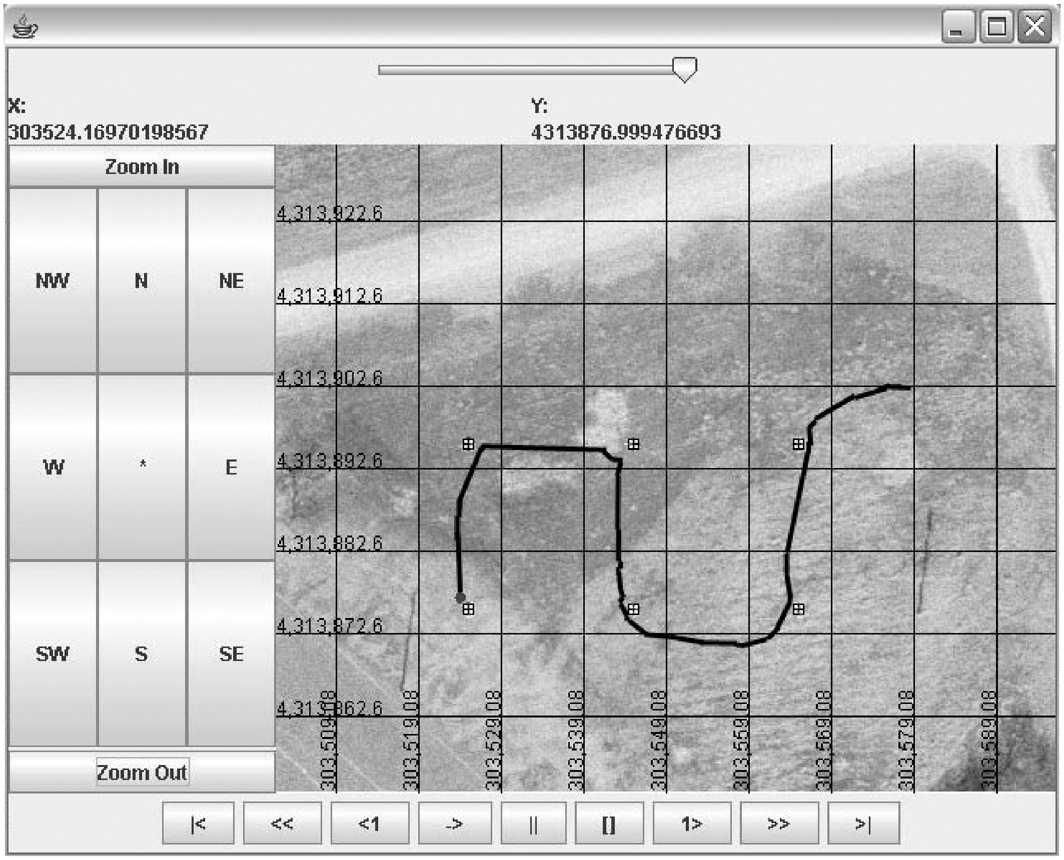
From these experiments, it is conclusive that with no filter applied to the MotionPak II, the TCM2 provides greater stability when measuring roll and pitch regardless of the level of vibration. The MotionPak II, however, provides consistent data when measuring yaw (heading).

9.5 Waypoint Navigation

Figures 9.8 and 9.9 present the path of the mobile robot while moving using waypoint navigation. Figure 9.8 presents a zoomed-in view of the local area with a grid scale of 10 meters. Figure 9.9 presents a zoomed-out view of the local area, including a view of Nichols Hall, a building on the campus of the University of Kansas. The path is plotted on a Geo-TIFF which is a satellite image of the local area that possesses position details relative to each pixel.

The waypoints are presented as boxes placed on the map with their centers located on the actual waypoint. The actual path is shown as the black line. Once the rover has successfully arrived at the initial position, it begins to perform the bistatic SAR navigation. As it can be seen from the figures, the rover passes within one meter of each waypoint. The heading sensors also work such that when the vehicle turns, it stops its turn once it is aimed in the general direction of the next waypoint, within a threshold.

During the 2004 field season, the thresholds for target arrival and turn angle

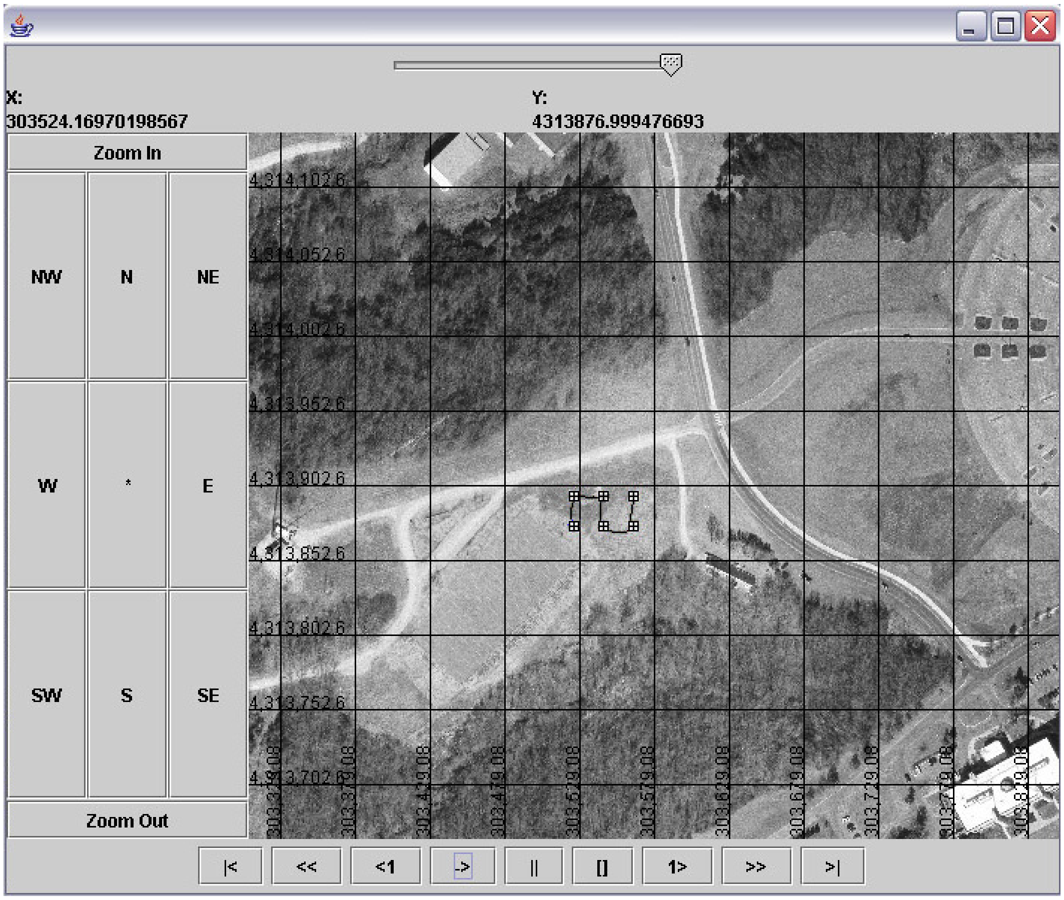


X:
303524.16970198567

Y:
4313876.999476693

Figure 9.8: Plot of rover's path while performing waypoint navigation.

will be adjusted so that these results will become even more precise and the path shall appear much closer to right angles.



X:
303524.16970198567

Y:
4313876.999476693

Figure 9.9: Plot of rover's path while performing waypoint navigation (zoomed out).

10. CONCLUSION

For decades, research in the polar regions has been of great interest for scientists. With issues such as global warming, study of the ice sheets provides a wealth of information to researchers in Earth Science, Atmospheric Science, Glaciology, etc. Research in these harsh environments can be quite challenging and dangerous to the human participants. Planetary and polar robotics are of great interest to researchers in these fields since they are capable of obtaining data with much less risk and reduced cost.

As part of the Polar Radar for Ice Sheet Measurement (PRISM) project, at the University of Kansas, a mobile robot was designed and constructed to support radar measurements in Greenland and Antarctica. The PRISM mobile robot was constructed using an ATV as a mobile base vehicle and building an environmental enclosure to support computer and radar equipment. The rover is designed to operate semi-autonomously with only limited human intervention.

This research has focused on the integration and evaluation of sensor modalities to support the PRISM rover, as well as other polar robotic endeavors. A general focus was to find commercial off-the-shelf (COTS) sensors. Prior to selecting the sensors, a literature search was performed to review existing sensor modalities. Existing polar and planetary rovers were analyzed to determine previous successes, failures, and limitations when operating in polar environments.

After reviewing the background, a set of criteria was developed to select sensor modalities. Given the rover's sensing needs, a suite of sensors was selected where each sensor met the needs of the PRISM rover as well as match the selection criteria. For positioning, a Topcon Legacy-E RTK DGPS system was selected that included a base station and two roving receivers. The LMS221 laser range finder was selected to measure the range of obstacles with respect to the rover.

The MotionPak II inertial measurement unit was selected to provide heading and tilt information. The TCM2-50 adds additional reliability to orientation measurements. The WS-2000 provides weather information for outreach purposes. The Pelco Esprit provides streaming video from the rover. Finally, the TL30 measures the rover's current fuel level for up to three gas tanks.

With the suite of sensors chosen, they were integrated with the PRISM rover. Integration of the sensors involved three main tasks of software integration, connectivity, and physical mounting. Software integration included the development of a software API for the PRISM sensors. Sensor fusion also took place within the software to provide additional functionality. Connectivity involved connecting all of the sensors with the necessary data links so that the information is properly shared. Mounting involved both external mounting of sensors as well as the construction of rack-mount cases for internal sensors.

The PRISM rover's sensor suite was next validated to demonstrate the survivability of the sensors, measure properties of the sensors not available from the specifications and data sheets, and verify correct operation, integration, and mounting of the sensor suite. To verify survivability, each sensor was tested during the Greenland 2003 field season to ensure that it could operate for an extended period of time in temperatures below 0° C. For external sensors, they must operate in harsher environments in Antarctica, a temperature chamber was utilized to test performance at -30°C. Properties of the Topcon GPS system were measured to ensure that it would provide reliable, accurate, and stable measurements while operating in the field. Finally, waypoint navigation demonstrated that the integration of the sensor suite can be utilized to provide intelligent and precise movements of the PRISM rover.

10.1 Contributions

This research provides a number of contributions to both the PRISM project and polar research. The sensor suite provides the precise navigation required to support the PRISM radar systems. The position measurements exceed the accuracy requirements by providing centimeter-level accuracy. Sensor modalities to detect obstacles have also been integrated into the PRISM rover. During future field experiments, these sensors can be easily integrated into the existing rover control system.

Polar researchers can also benefit from the research presented in this thesis. The suite of sensors was built entirely from commercial off-the-shelf sensor modalities. These sensors have been tested and proven reliable in polar environments. Researchers who wish to automate their own polar research can utilize the knowledge provided in this thesis.

10.2 Limitations

The software suite and its integration are not without limitations. Key issues are: crevasse detection, obstacle avoidance, fuel level sensing, and sensor fusion.

By validating the performance of the sensor suite, it was concluded that we could not safely or reliable detect crevasses. Since such negative obstacles are often undetectable to both vision and ranging systems, the integration of an additional radar system may be necessary. For now, crevasse detection is not critical because of the information provided prior to entering the field regarding such hazards. However, the vehicle would not be able to safely conduct research remotely in the field without human presence nearby.

For the Greenland 2004 field season, obstacle avoidance had not been integrated with the PRISM rover. We have been capable of validating that the sensor is capable of detecting obstacles. The development and implementation of an avoidance algorithm is necessary to integrate obstacle avoidance with the rover's current control system.

For safety reasons, the TL30 fuel sensor was not utilized during the 2004 field season. The sensor arrived to late in the Spring of 2004. Given time constraints based on shipping dates, it would not have been feasible to install the sensor prior to departure.

The sensor fusion discussed in this research is still at a crude stage. For this research, simple thresholds and events were utilized to determine how to switch between sensors whenever redundant sensor values were available. Numerous algorithms and techniques exist to fuse sensor data.

10.3 Future Work

Given the current state of the PRISM sensor suite, there are multiple tasks that must be carried out to further advance the development of the PRISM mobile robot and its sensor suite.

Development of the PRISM rover's software library can add reliability and efficiency to the overall system. Additional fault tolerance could aid the rover whenever a sensor temporarily fails or provides faulty or noisy data. Development of more advanced sensor fusion techniques can aid the rover in ascertaining its current state and provide more reliable analysis. Obstacle avoidance must be developed and integrated with the waypoint navigator such that the rover can make a best effort to follow a set of waypoints while avoiding whatever obstacles it encounters.

Additional sensor modalities may be explored to add sensor redundancy. Investigation into Millimeter-Wave Radar and Ground Penetrating Radar can be made to provide crevasse detection. Computer vision will be investigated as an aide to obstacle avoidance. The use of stereo and thermal imaging may provide worthwhile data to support the laser range finder by providing additional data.

Such data could help determine the obstacles size, density, and other relevant features.

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