

Design and Simulation of a Polar Mobile Robot

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ABSTRACT

This paper describes the design and simulation of a mobile robot for missions in polar regions. The robot was designed to provide mobility, power, precise positioning and environmental protection for a bistatic synthetic aperture radar for polar regions to measure ice thickness and other ice sheet characteristics. The robot is required to carry and protect the radar system and to tow a large antenna, while providing precise positioning of the antenna to the accuracy of within a few centimeters. In parallel to the design and fabrication of an actual robot, a simulation model of the robot was designed and a virtual prototype was built to perform numerous experiments without the need for actual deployment in polar regions. These experiments tested robot characteristics such as slopes in the terrain, rolling effects, turning radii, antenna attachments, and payload distribution.

KEYWORDS

polar robots, Mobile robots, robot simulation

1. INTRODUCTION

PRISM, or Polar Radar for Ice Sheet Measurements (www.ku-prism.org), was started with the goal of measuring characteristics like ice thickness and for determining the conditions of the rock underneath the ice sheets in the polar regions of

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Greenland and Antarctica. The data generated from this project can help scientists more accurately determine the effect that the melting of the polar ice sheets has on the rise of the sea level. Because approximately sixty percent of the Earth's population lives in coastal regions, a significant rise in sea level can have a devastating impact, which makes this type of data essential for identifying trends and forecasting future changes. This is a project that requires many different technologies working together to achieve its goal—including radar, GPS, wireless communication over long distances, and an autonomous vehicle intelligent and robust enough to survive for long periods in a harsh environment. A number of faculty, technical staff, and many graduate and undergraduate students are working together to successfully design, build, and integrate these technologies and to help the project meet its goals.

The radar for this project is a new design in which the radar consists of two parts that must work together to measure accurately the thickness of the ice. Each part of the radar also requires an antenna. The two parts of the radar, at times, will have to be a great distance apart to work properly. To have the radar in the proper position, a rover vehicle will be used to carry it, and to make this as efficient as possible, the rover vehicle control will be automated. Automating the rover allows it to work for long periods non-stop and also minimizes the 'footprint' that many people performing the same job would have on the environment. This automation also lessens any concerns for the safety of the individuals that would have to control the rover manually. The rover has several tasks to complete when deployed, the most important being to move the radar and antenna to precise locations. But, to be successful, the rover must also negotiate dangerous terrain and employ several other self-preserving skills to last in the harsh polar environments for long periods without human intervention.

The mission of the robotics group of PRISM is to design and build a rover to carry the radar and tow the antenna. The group has to make many design decisions about the rover vehicle, such as electric or gas powered engine, the type of vehicle, track or wheel, and many others. Each decision also brings with it other concerns, which may or may not yet be known. These design decisions have to be made with only a general specification of the radar and antenna that has to be towed, as they have not been fully implemented nor designed. This paper describes how the model of the rover was created and the tests that were performed on the model. The testing is intended to determine how well the model performs such basic tasks as pulling the antenna while turning and what slopes the rover can climb. This information is necessary for the builders of the rover, as the rover must be created to traverse potentially harsh terrain.

2. RELATED WORK

2.1 Modeling of a Snow Track Vehicle Research

Research at the University of Perugia in Italy (Braccesi et al., 2002) focuses on the analysis and the design of snowmobiles and ways to improve the design. The researchers use the ADAMS software to build the model of the snow track vehicle and test it (www.adams.com). This paper presents an overview of the model and the analysis of all the different parts of the snow track vehicle. The components that were modeled and tested include the track, suspension, frame, upper structural components (cabin and motor), auxiliary rope traction system (winch), front snow shovel, and the rear snow-crushing device. The paper describes how some specific components were modeled and discusses the dynamic analysis of the model. The model and its components were tested on plane ground, rough ground, a 15-degree slope, and a 30-degree slope. The results include the histories of data such as the track force, gear angular velocity, the velocity of the vehicle, and much more. This paper provides a good idea of how different components can be modeled and tested and of the data that are available from doing this kind of testing.

2.2 Simulation of a Three-Wheeled All Terrain Vehicle

Researchers at the University of Arkansas (Lim & Renfroe, 2002) describe the danger of three-wheeled ATVs and their handling ability. These ATVs have always been known to be dangerous and consequently have a significant amount of accidents. This paper attempts to demonstrate the handling and suspension characteristics of the three-wheeled ATV. This paper presents their model and analyzes the lateral stability of the ATV. It is argued that the three-wheeled ATVs were meant for average users, and why the results of their testing show that the three-wheeled ATV does not handle well enough for average users.

2.3 Modeling Tracked Vehicles Using Vibration Modes

This paper by researchers at the University of Michigan develops a full-tracked vehicle model and suspension in an attempt to predict the durability of the track, as well as the vibration inside the vehicle caused by the tracks (Scholar et al., 2002). The researchers

developed a model of a tank with which several different track models could be used. Some of the models include static (spring-damper), dynamic model with longitudinal vibration, dynamic model with transverse vibration, and dynamic model with coupled transverse/longitudinal vibration. The vehicle simulations were run over a 0.25-mile track with many bumps ranging from 30.5 cm high and 762 cm long to 7.6 cm high and 91 cm long. The model moved over the course at a speed of 25 miles per hour. The vibrations caused by the track stem from how the track handles while moving over bumps, so the researchers could determine which track models tend to cause fewer vibrations. Results from the simulations are given for the static track model as well as the dynamic model with coupled transverse / longitudinal vibration.

2.4 Simulation of the Hybtor Robot

The research project at Helsinki University of Technology describes the simulations used to study the load balancing and stability of the robot (Aarnio et al., 2002). Two models were used, a kinematics model and a dynamic model. The dynamic model was the same as the kinematics model, except that dynamic properties such as mass, inertia, and ground contact forces were added to the model. The kinematics model was used only for locomotion visualization and monitoring purposes. The dynamic model was used for torque and stability analysis.

2.5 Virtual Prototyping of the Suspension System of an All-Terrain Vehicle

The research paper from the State University of New York describes the details of how they used MSC.visualNastran 4D to perform tests intending to help them create an all-terrain vehicle suspension (Khoo et al., 2002). The authors discuss the many tests and give many images from the simulations they run that led them to the design, beginning with a single tire, and ending with a full suspension.

2.6 Digital Simulation of an Aerospace Vehicle

The research for this work was conducted at Marshall Space Flight Center in Huntsville, Alabama Mitchell *et al.*, 1967). The purpose of this paper was to describe the Aerospace Vehicle Simulation Program (AVS) and how the program could help in the development of aerospace vehicles, as far as the design and

checkout of the vehicles is concerned. The paper also describes that many people are continuously working on the vehicle making changes. Such changes can cause a detailed analysis to be performed, which is very time consuming, and how the AVS software can help them rapidly speed up the design and checkout process of the aerospace vehicles.

2.7 Khepera Simulator

The Khepera Simulator is a package developed in Switzerland that allows developing of controllers for the Khepera robot (Michel, 2002). The simulator gives a two-dimensional display of obstacles, and the sensor values are shown while running. The software allows for easily transferring the controls from the simulated robot to the actual robot. The controllers are developed using C and C++ and the package is intended for teaching and researching autonomous agents.

2.8 Webots

The Webots simulator is a newer, commercial version of the Khepera Simulator, developed by Cyberbotics (www.cyberbotics.com). This simulator is similar to the Khepera Simulator but now has a three dimensional view of the robot. The software also includes a rapid prototyping environment that allows for modeling the robots and simulating any robot, not just the Khepera robot (Michel, 2002). Examples of other simulations and studies include Webots Dynamics (2002), Thornton (2002), MissionLab (2006), and Bares and Wettergreen (1999).

3. MODEL DESIGN

This section describes the design and the model used for testing. Each aspect of the model, including the rover, antenna, towing mechanism, and terrain is described.

3.1 Environment and Terrain

Most of the terrain that the vehicle is used in is flat. Yet, the landscape in the polar regions can change very quickly. The terrain can be very dangerous, and the vehicle

will eventually have to explore a large area of Greenland and Antarctica. The landscape modeled in the software has been limited to flat ground without large bumps or obstacles. The slopes the model climbs during the tests applies to them as well. The environment modeling has been limited to using a coefficient of friction of 0.3, a commonly chosen value for tires on snow, which is very limited in that the polar terrain is not just snow. In some areas such as those with ice, the coefficient of friction could be much less, and in some areas could be much more. We chose 0.3 as an estimate of the average coefficient of friction that will be encountered. The modeling of the ground with only a coefficient of friction does not model how the vehicle performs when traveling over large bumps or other obstacles. This has been left for testing at a later time.

3.2 Rover Base

The vehicle used as the rover base is Buffalo Max All-Terrain Vehicle from Recreative Industries (www.maxatvs.com). It is a six-wheeled amphibious ATV, as shown in Figure 1. The specifications of the Buffalo Max ATV are listed in Table 1. The frame, as seen in Figure 2, was built to hold all the equipment needed in the vehicle and protect it from the weather. The frame was built using T-Slotted aluminum bars. The solid panels are made from alucobond, and the clear panels are made from hyzod. All were purchased from the company 80/20 (www.8020.net).



Fig. 1 Original Buffalo Max ATV.

TABLE 1

Specifications of Buffalo Max ATV as listed in (Recreative Industries Inc., 2002)

Dimensions	Centimeters
Length	251
Height	132
Width	145
Wheelbase	147
Bed Length	140
Bed Width	127
Bed, High	46
Weight	Pounds
Dry Weight, no accessories	900
Gross Trailer Weight	1000
Tracks	222
Winch Plate	9
Winch	22



Fig. 2: The rover in Greenland.

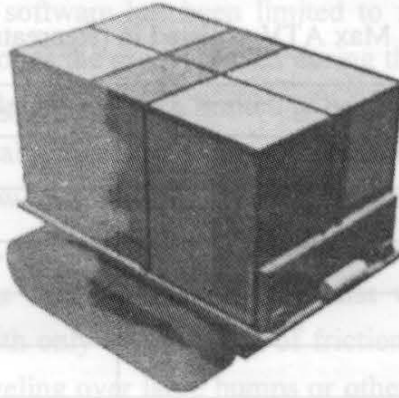


Fig. 3: Image of the final track vehicle model that was used for each experiment

The frame was modeled as closely as possible to the actual frame, with the exception of the shape of the aluminum bars, which were modeled simply as cubes. Modeling the actual shape was not necessary, as this would add extra complications to the modeling, and the material itself was not being tested, only the frame's size and weight were needed to test the model. The weights of the materials were taken from (80/20, 2002) to ensure that the weight of the frame was as accurate as possible.

The model of the vehicle (Figure 3) was created using the specifications from Table 1. The model was created as close to the actual vehicle as possible. Where sizes were not given in the specifications, actual measurements were made. The shape of the vehicle was modeled using mostly cube objects. The cubes were given the appropriate weights for the location. The engine, for example, was placed behind the cab and given the weight as specified.

The model does not perfectly match the actual vehicle, however, as there are many shapes and contours that are difficult and unnecessary to model. Additionally, the weight distribution of the vehicle was not completely known. Nevertheless, the overall weight, and the weight of the options that came with the vehicle were known along with the engine. Where objects like the engine had known weights, that weight was placed in the approximate location in the model. Objects such as the winch and track also had known weights and locations. Otherwise, the weight of the vehicle was evenly distributed around the base of the vehicle.

The tracks were modeled and simulated using the conveyer object belt type in the software. The conveyer belt object fits the track shape almost perfectly. Each conveyer belt contains its own motor, so speed is controlled using two motors. This

is the main difference between the model and the actual vehicle. The actual vehicle has six-wheeled drive and a patented skid-steer transmission for movement. For simplification purposes, a transmission was not created for the model. Instead, the two motors have to be set to different speeds when causing the vehicle to turn, and the same speed when going forward. The motor speed for each could be set in many different ways such as specifying a speed at a given time and inputting a function with respect to time. Many different types of functions could be used, for example, step functions, ramping functions, and allowing the software to interpolate between given speeds at given times with linear or polynomial functions. These different options allow us to test different methods of turning the rover.

The control is similar to how Marvin is actually controlled, at least from the navigation system's point of view. Steering the vehicle is done with two handles, one for each track on the vehicle. Either side can be engaged or disengaged at any time. The motors for each side of the vehicle represent the handles to control the actual vehicle. When the motor on the left side is running, the left side is engaged. The same is true for the right track and motor. The objects that made up the model were usually attached with a rigid constraint. The solid constraint caused the software to treat both objects as a single object. Another version of the model, a six-wheeled version, was much more complex than the track version. The six-wheeled version required the wheels to be attached with a revolute constraint that allowed rotation around one axis. The wheels on each side were then constrained with a belt so that each side would turn at the same rate. The front wheel on each side was given a motor that replaced the revolute constraint and that could be given the same parameters as the conveyer belt. The tracked model was much simpler than the six-wheeled version. Each constraint could then be monitored during simulations for the amount of force that was being applied to it. This helps us to determine if, and when, the frame or other objects that we have built or are designing need to be changed. For example, the frame is attached to the base of the rover in only a few locations. Some of the objects being placed on the frame are very large and heavy, and we can determine how much force they are applying to the frame on those points when the rover is driving uphill.

3.3 Antenna

The antenna specifications have been the least specific of any element designed so far. The model for the antenna was therefore created simply as a flat rectangular box

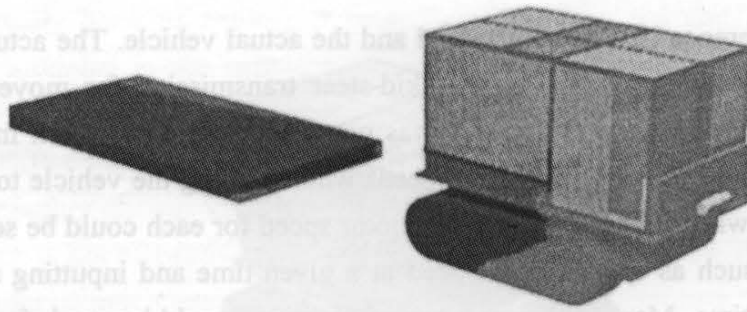


Fig. 4: The rover with 2 meter by 4 meter antenna. The towing mechanism used was not rendered by the software because it is a constraint in the software program, and the constraints are not rendered.

as shown in Figure 4. The box can be resized easily, and so can the weight through parameter setups. The current maximum specifications for the antenna are dimensions of 4 by 2 meters and weighing 400 pounds. Because of uncertainty in the antenna size and weight, three antennas were decided upon that would be tested. Figure 4 includes a picture of one of the antennas. Table 2 lists the specifications of each antenna.

TABLE 2

Specifications for the three antennas

Antenna Option	Width (meters)	Height (meters)	Weight (pounds)
1	4	2	400
2	2	4	400
3	2	2	200

3.4 Towing Mechanisms

Four different towing mechanisms were used for each antenna type, namely, a single rope, two ropes, a single rod, and two rods. The rod and rope are defined as a constraint in the simulation software. In other words, they act to constrain two object in a specific way, but they are not physical objects. Therefore, they are also not rendered within the images. Each mechanism is described in this section.

Single Rope: The rope constraint acts to keep the constrained object a maximum distance apart in any direction, from the point where it is attached. The objects

constrained are allowed to rotate on the point where they are attached. This allows the antenna to slide into the vehicle when moving on a steep downhill.

Two Ropes: Each rope in this mechanism acts as the single rope, but the ropes are attached to the antenna on the far edges of the antenna, and the same location on the vehicle. This constraint was used to keep the antenna parallel to the vehicle, as a single rope would allow the antenna to turn more easily.

Single Rod: The rod constraint is similar to the rope constraint, except that the two objects constrained are kept at a specific distance, not just a maximum distance apart, where the constraint is located. The idea with this constraint is to keep the antenna from colliding with the vehicle, which the rope would not do.

Two Rods: This mechanism is used for the same reason as two ropes, except that the antenna is kept a specific distance from the vehicle, not just a maximum distance.

3.5 Load Distribution

At this time, several equipment and parts have been identified, and their placement inside the vehicle must be determined. There are three locations in the vehicle to load up to 900 pounds. Currently, there is a generator, PCI chassis boxes for the radar system, and some equipment to control the sensors and guide the vehicle. Where these items are placed can have a large effect on how well the vehicle handles and can change some of the safety parameters for the vehicle. Therefore, the model also has to be tested with some different possible load distributions, as the weight being put into the vehicle is a significant amount. To place the load distribution into the vehicle, three boxes were placed into the perspective locations shown in Figure 5.

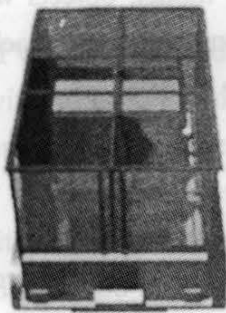


Fig. 5: Load distribution image with top cut away. The image shows where the load was placed into the vehicle. The top panels have been removed so that each box can be seen easily. The blue box is actually sitting on the front seat, and is smaller than the other two. Each box's weight is set to a different value depending on which load distribution is being tested.

TABLE 3

Load distribution weights. Load distribution weights for each of the three load distributions used in the experiments.

Distribution	Front (pounds)	Middle (pounds)	Back (pounds)
1	100	400	400
2	100	500	300
3	200	400	300

Three different load distributions were decided on that would be tested (Table 3). These distributions seem the most plausible with how the vehicle is currently set up.

3.6 Simulation Package

MSC.visualNastran 4D was used for both the modeling and the simulations (MSC Software, 2002). For modeling the vehicle, several object types are given in the software: sphere, cube, cylinder, conveyer belt, and extrusion. The extrusion is used to create more-complicated object types. These were used minimally. Objects can be constrained together in many different ways. To constrain these objects, the software uses an item called a constraint. The constraint allows, or disallows movements in one or more directions. Some different types of motion are rotation in one or more directions, linear motion, sliding, and many more. Rigid constraints are used to place together two objects that do not move. This approach allows the software to consider the two objects as the same. There are also motor constraints that can be used to cause movement in different directions at set or variable speeds. There are other types of constraints allowed in MSC.visualNastran 4D. To generate the model, objects were created as closely as possible to the actual vehicle, then given constraints and attached to other objects. This allows for the movement of the tracks on the vehicle.

3.7 Evolution of the Model

The first models of the rover were generated based of vehicles that the PRISM group was considering as possible solutions. The first two models were of a four-wheel

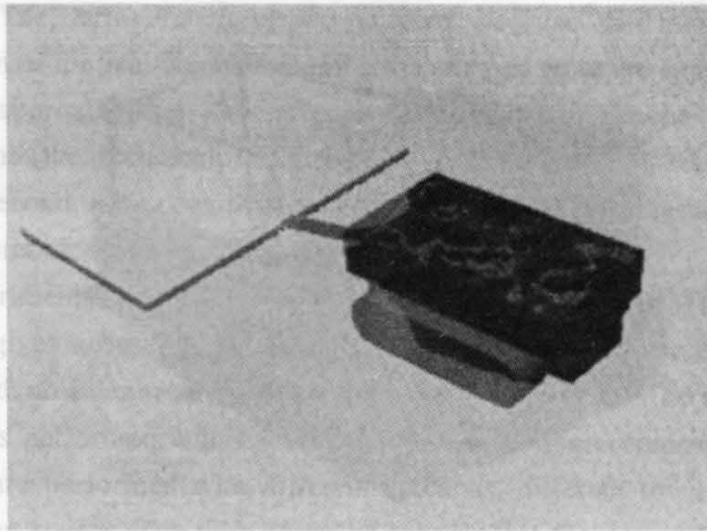


Fig. 6: Models of possible rover vehicles.

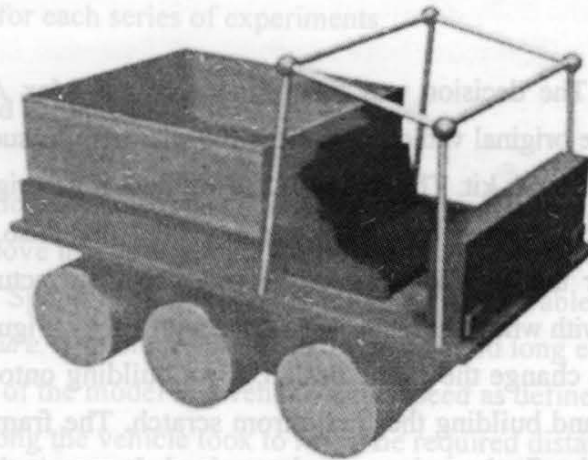


Fig. 7: Model of the six-wheel vehicle before modifications.

ATV and a tracked ATV 6. These were created as simply as possible, while still trying to keep the dimensions as accurately as possible. Little experimentation was performed using these models.

The models were created with the idea that they would be used to communicate with the radar researchers which vehicles were being looked at as possible solutions. They would also be used illustrate the type of testing that could be done using the simulation software. Neither of these two models however, was chosen as the vehicle

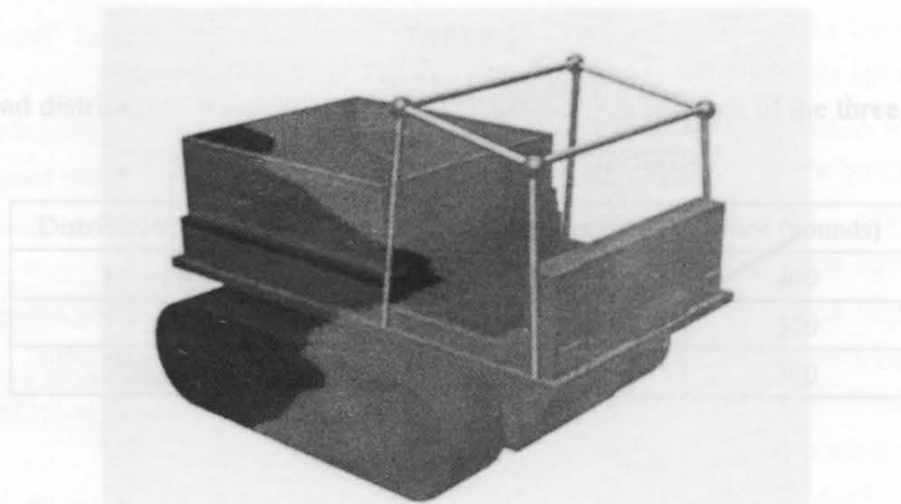


Fig. 8: Model of the track vehicle before modifications.

to become the rover. The decision was finally made on the Max ATV All-Terrain Vehicle (Figure 1). The original vehicle was available with options such as a roll-cage, a front window, and the track-kit. The roll-cage and window were originally thought to be a part of the final vehicle, and these were modeled originally. Also, it was uncertain whether the wheels or the track-kit were to be used, so there actually existed two different models, one with wheels (Figure 7), and one with tracks (Figure 8).

It was decided to change the frame design, from building onto the roll-cage to removing everything and building the frame from scratch. The frame itself changed several times before the final version was determined. It was at this time that the track-kit was used on the vehicle, and it was decided to choose the track option over the wheels. For a while, the design of the vehicle was in a constant state of change. The final version is what has been tested in all the simulations. There is no guarantee that the current vehicle will be used as a final solution for the PRISM project. Therefore, the current model may not be the last one either.

4. EXPERIMENTS

The experiments performed were designed to answer some specific questions about the performance of the rover. First, what should the starting point be for the safety

parameters? The term *starting point* is used because the model is only an approximation of the real world, therefore, the answers from the experiments should only give an approximation. The safety parameters include the maximum slope the rover can climb (the pitch angle) and the point at which the rover might roll over (the roll angle). Second, how does the rover handle while performing basic movements and with different load configurations?

The experiments are grouped into three series of experiments. The first series of experiments gives a baseline of how the model performs. These experiments are performed with no antenna and without any load on the vehicle. The second series of experiments is performed with the antennas and towing mechanisms. The antenna experiments are performed with different antennas, different towing mechanisms, and at different speeds. The third series of experiments focuses on the rover with a single antenna and fully loaded. Three different load configurations were chosen that have been tested. Following is a description of the experiments. The experiments are performed once for each series of experiments.

4.1 Flat Ground Experiments

This one is a basic experiment that acts as a control group for some of the other tests. The rover will move in a straight line for a set distance at a set speed.

Parameters. Speed: 10 km/hr; Distance: 15 m; Measurable: Time (seconds).

Test Procedure. The model is placed on flat ground long enough to complete the test. Each motor of the model is given the same speed as defined. The test is timed to determine how long the vehicle took to reach the required distance.

Evaluation. The results will show how the vehicle performs in normal operating conditions, and how much slippage, if any, occurs. If no slipping occurs, the vehicle should be able to complete the operation in about 2.8 seconds.

4.2 Maximum Slope Experiments

This test determines the maximum slope (i.e. pitch) the vehicle can successfully climb.

Parameters. Speed: 10 km/hr; Slope Distance: 15 m; Measurable: Slope (pitch angle (degrees)).

Test Procedure. The model is placed on a flat ground approximately 5 m before

the slope begins. The slope of the ground is increased for each test until the angle is found that the model cannot successfully traverse, or traverse within a reasonable amount of time. The angle that the model can traverse is found to the nearest degree.

Evaluation. Each test is considered successful if the model can move up the slope the required distance, and within a reasonable (less than a minute) amount of time. The test is considered unsuccessful if the model cannot move up the slope at all, or cannot traverse the required distance.

4.3 Roll Experiments

This test will determine the maximum roll angle that does not cause the model to roll over. This test provides a good approximation of safe parameters to run without tipping over.

Parameters. Speed: 0 km/hr; Distance: 0 m; Measurable: Roll Angle (degrees).

Test Procedure. The model is placed on ground facing the y-axis direction and is rotated around the y-axis.

Evaluation. A test is considered successful if the vehicle falls in such a way as to land on the tracks. The test is considered unsuccessful if the vehicle rolls onto its side. After each successful test, the roll angle is incremented until an unsuccessful test occurs. The previous angle is considered the maximum roll angle.

4.4 Radius Experiments

This test provides an approximation of the turning radius of the model in one direction. The turning radius is assumed the same in both directions.

Parameters. Measurable: distance from origin (meters); Right Track Speed: 1· Left Track Speed: 10, 8, 6, 4, 2.

Test Procedure. The model is placed on flat ground with a large enough area to accomplish the test. One test is performed for each specified track speed. The start location is at the origin with the model facing in the y-axis direction. The end location is determined by the location the model is at when its angle is facing in the negative y-axis direction.

Evaluation. There is no successful or unsuccessful test, i.e. each test continues until the model faces in the opposite direction.

The turning radius is calculated by determining the distance from the start

location to the end location. This test is mainly a visual test, therefore graphs and pictures are used to show the results of these tests.

5. EXPERIMENTAL RESULTS

5.1 Turn Radius Experiment Results

The data from this experiment are numerous, so only a few examples will be shown. Figure 9 shows a sample of the model pulling the antenna with a single rod, and the model pulling the antenna using two rods respectively. The figures show the final result of the simulation when the rover had completely turned around.

Figure 10 shows a sample of the model pulling an antenna at 10 km/hr and 2 km/hr. The graphs show the position of the antenna and rover, as well as the orientation of the antenna. This gives a good indication of the required distance the turn requires, and how well the antenna turned around. The results show that the antenna towed at 10 km/hr did not turn very well. The antenna did not turn very much compared to the antenna towed at 2 km/hr. This is a result of how the rover turns. With the rover turning so quickly, it has a tendency to turn in place. The rover moving at 2 km/hr required approximately twice the distance to turn around as the rover turning at 10 km/hr. turn requires, and how well the antenna turned around.

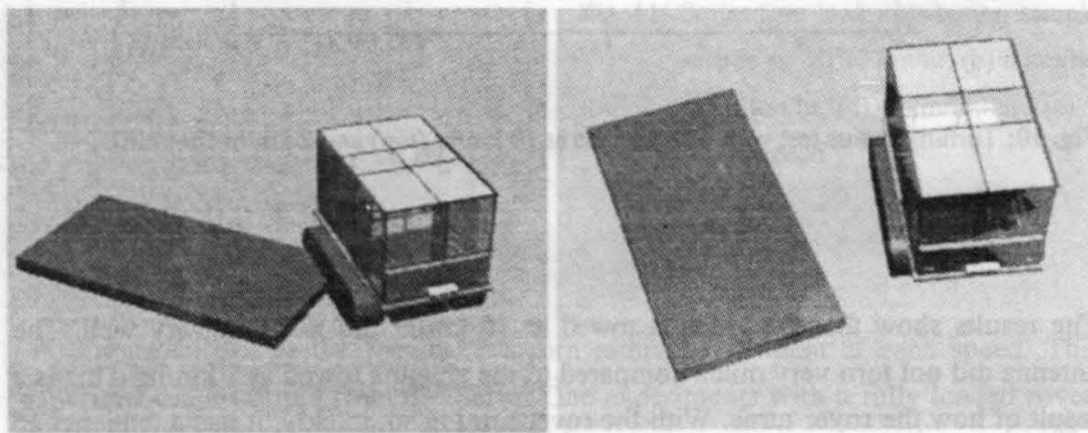


Fig. 9: Turning radius test with 4x2 antenna and (top) single rod (bottom) two rods.

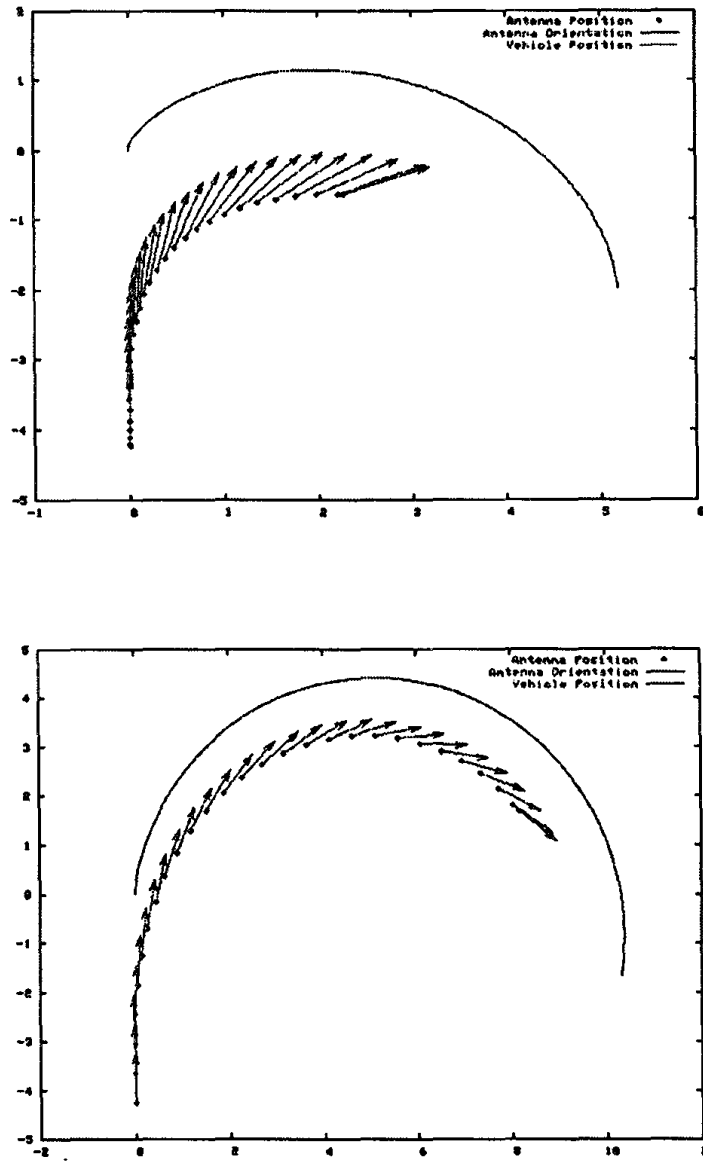


Fig. 10: Turning radius test with 4x2 antenna at 10 km/hr (top) and 2 km/hr (bottom).

The results show that the antenna towed at 10 km/hr did not turn very well. The antenna did not turn very much compared to the antenna towed at 2 km/hr. This is a result of how the rover turns. With the rover turning so quickly, it has a tendency to turn in place. The rover moving at 2 km/hr required approximately twice the distance to turn around as the rover turning at 10 km/hr.

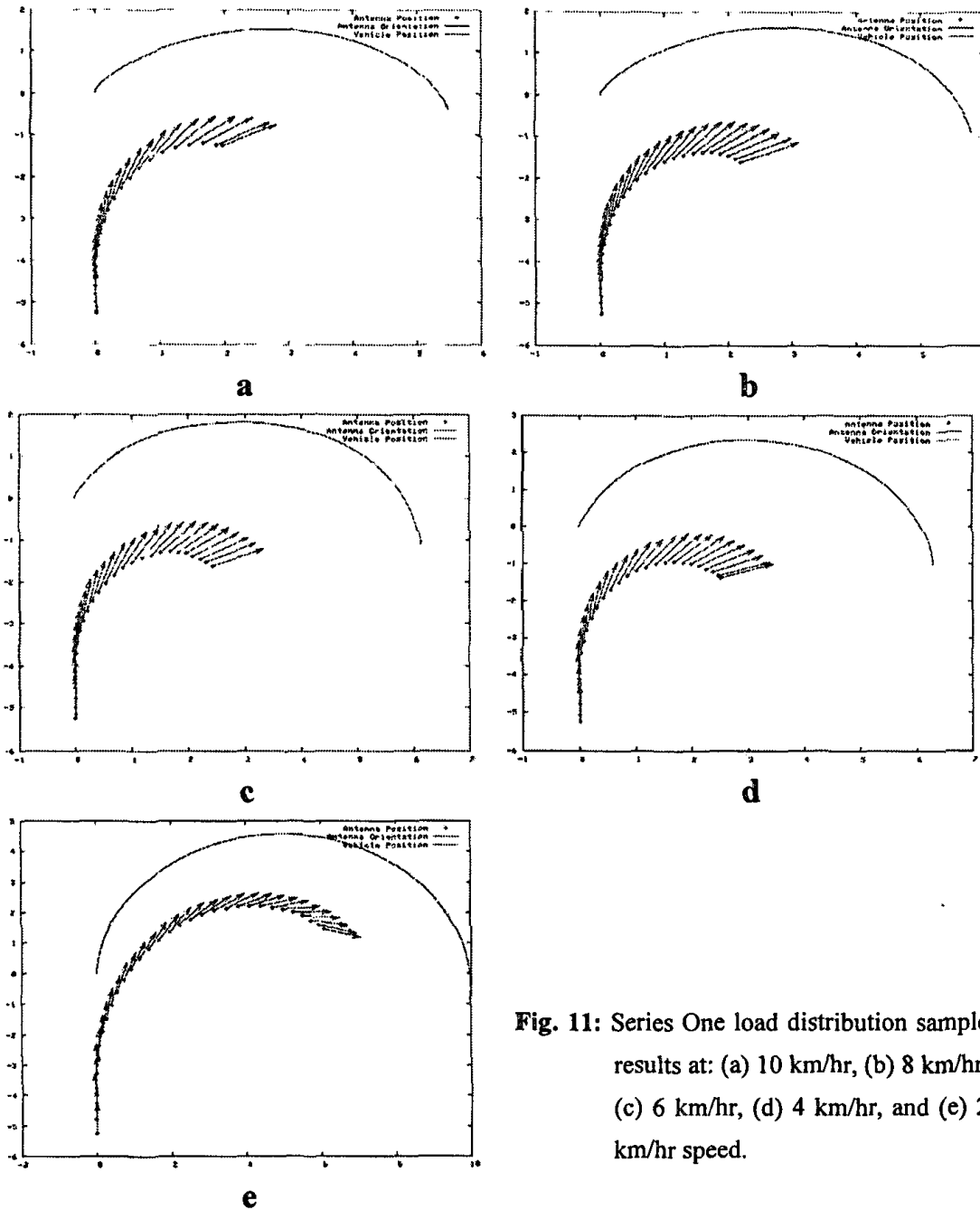


Fig. 11: Series One load distribution sample results at: (a) 10 km/hr, (b) 8 km/hr, (c) 6 km/hr, (d) 4 km/hr, and (e) 2 km/hr speed.

Figure 11 shows the results of a turn radius experiment at each speed. This experiment is a sample from the Series One experiments with a fully loaded rover. Testing with a single rope or a single rod sometimes produced erratic results. The antenna did not always turn at the same rate as the vehicle did, causing the antenna to face in different directions. The two ropes and two rods towing mechanism forced

TABLE 4

Series One testing summary

Test	Result
Flat Ground Testing	5.88 seconds
Maximum Slope Testing	18 Degrees
Maximum Roll Testing	58 degrees

the antenna to turn more with the rover most of the time. However, they sometimes had the same problem as the single versions because the rods and ropes are free to move at any angle with respect to the point at which it is attached. If the rods or ropes constrained in such a way that they did not have this freedom, then the antenna would turn much better and this problem, as shown in Figure 10, would not happen. A better towing mechanism can be constructed and tested, but for this series of tests, only rods and ropes were used.

5.2 Other Testing Results

This section gives a summary of the results for the other tests described, flat ground testing, maximum slope angle, and maximum roll angle.

Track Vehicle Experiments. Table 4 lists a summary of the results for the Series One track vehicle experiments.

Antenna Experiments. Tables 5, 6, 7, and 8 list the summary of the results for the antenna experiments with a single rope, two ropes, a single rod, and two rods, respectively. The tables show that the results varied very little when comparing the 2x4 and 4x2 antennas. The 2x2 antenna experiment results were much improved over the other antennas as expected.

Payload Distribution Experiments. Table 9 lists a summary of the results for the Series Three payload experiments. The table shows that the maximum roll angle decreased as expected, the results improved for the other two experiments.

The results from all three series of tests are mostly as expected. Series One tests performed better than the other series' tests. The rover was neither weighted down nor dragging an antenna. Therefore, it was able to climb a steeper slope and perform the flat ground test in a faster amount of time.

TABLE 5

Series Two testing summary with single rope

Test with single rope	2x4 Antenna	4x2 Antenna	2x2 Antenna
Flat Ground Testing	6.26 seconds	6.24 seconds	6.02 seconds
Maximum Slope Testing	10 degrees	11 degrees	14 degrees
Maximum Roll Testing	58 degrees	58 degrees	58 degrees

TABLE 6

Series Two testing summary with two ropes.

Test with two ropes	2x4 Antenna	4x2 Antenna	2x2 Antenna
Flat Ground Testing	6.24 seconds	6.24 seconds	6.02 seconds
Maximum Slope Testing	11 degrees	11 degrees	14 degrees
Maximum Roll Testing	58 degrees	58 degrees	58 degrees

TABLE 7

Series Two testing Summary with single rod.

Test with single rod	2x4 Antenna	4x2 Antenna	2x2 Antenna
Flat Ground Testing	6.24 seconds	6.24 seconds	6.02 seconds
Maximum Slope Testing	11 degrees	11 degrees	14 degrees
Maximum Roll Testing	58 degrees	58 degrees	58 degrees

TABLE 8

Series Two testing Summary with two rods.

Test with two rods	2x4 Antenna	4x2 Antenna	2x2 Antenna
Flat Ground Testing	6.24 seconds	6.26 seconds	6.02 seconds
Maximum Slope Testing	11 degrees	11 degrees	14 degrees
Maximum Roll Testing	58 degrees	58 degrees	58 degrees

TABLE 9

Series Three testing summary

Test	Load 1	Load 2	Load 3
Flat Ground Testing	6.06 seconds	6.06 seconds	6.06 seconds
Maximum Slope Testing	13 degrees	13 degrees	13 degrees
Maximum Roll Testing	46 degrees	46 degrees	46 degrees

5.3 Discussion

The maximum slope testing, however, improved from Series Two to Series Three because the added weight in the rover in Series Three was helpful when pulling the antenna up the slope. We can conclude from these experiments that the rover must have some weight in the back if it is towing an antenna and if it is going to perform to its maximum abilities. The results do not show if an improvement could be made with the 2×2 antenna as the Series Three experiments did not use such an antenna. The maximum roll testing from Series One and Series are the same in all tests. This is a result of the towing mechanism not being rigid at its point of contact. If the towing mechanism were rigid, then the results would most likely be different, but the weight of the antennas did not force the rover in one direction over the other and therefore did not change the results.

The results did change very much in the Series Three experiments because a significant amount of weight was added to the back of the vehicle. The results changed from 58 degrees in Series One and Series Two to 46 degrees in Series Three. The added weight also dramatically changed the center of gravity of the rover because the weight was placed so high in the vehicle. Because the boxes of weights were added with a rigid constraint, they acted as a part of the rover and caused it to tip over at a much smaller angle.

The turn-radius experiments showed that a towing mechanism better than the ones tested could be needed. Turning for all mechanisms performed much better at 2 km/h than at the top speed of 10 km/h, as was expected. However, if the towing mechanism were constrained at the point on the rover so that it were not allowed to move, then the problems associated with the antenna turning in a direction different from that of the rover (see Figure 10) would be solved. This also leads to the

conclusion that if it were to contact a large bump or hole on one side or the other, the antenna's orientation could be severely changed. Going extremely slowly over the bumps might not solve this problem.

The rover was successfully tested in Greenland during the Summer of 2003.

6. CONCLUSION

6.1 Contributions

The experiments described here show that the rover is a suitable vehicle for towing the large antennas, based on the requirements from the radar team. The simulations show that the vehicle can perform adequately in the desired areas of use. The results from this project will help researchers of the PRISM project to make decisions on how much equipment the vehicle can carry and the placement of the equipment within the vehicle. The results give a good approximation of the different slopes that the vehicle can handle in different situations, such as the antenna weight and size and the different loads that the vehicle is carrying.

The enclosure of the vehicle is somewhat heavy, at around 150 pounds. This added weight does not seem to impede operation of the vehicle but may actually improve its operation when towing an antenna behind the vehicle. Testing was not done to determine how much the structure affects the maximum roll angle of the vehicle. If it is desired that the vehicle must be more stable with respect to the maximum roll angle, then the enclosure may have to be redesigned, or built with lighter material. However, given the equipment load that will be placed in the enclosure, the weight of the enclosure is likely to be insignificant compared to this equipment.

The testing results also give a good indication of how the vehicle will turn and of the best ways to turn the vehicle without damaging the antenna. All these approximations were found without the need of physically testing the vehicle.

6.2 Limitations

The main limitation with this work is the terrain. The terrain could not be modeled perfectly. The flat terrain works for testing many concepts, but does not show how

the vehicle handles in rough terrain with large bumps or holes.

The tests also do not account for such environmental conditions as wind. The gusts of wind in Antarctica can have a large effect on how the vehicle handles, especially the Maximum Roll Angle tests.

The model itself can be a problem, which creates inaccurate results. The weight distribution of the actual rover is not completely known, and large differences between the model and the rover can cause the testing to be inaccurate.

The model was also limited in its accuracy because of the tracks. Each track has its own motor, where the rover only has one. This means that testing concepts like torque would not be accurate; however, testing the dynamics was not apart of this project.

6.3 Future Work

More work must be done to see how the vehicle handles large bumps, holes in the ground, and rough terrain in general. Rough terrain in simulation packages such as MSC.visualnastran4D is difficult to model. Instead, the terrain could be better modeled in another program that is designed specifically for modeling. Then it could be imported into the simulation package.

To improve the safety parameters from this testing further, the tests could be performed with wind pushing on the vehicle from different directions. The gusts of wind can change the ability of the rover to climb slopes or to keep from rolling over.

A different towing mechanism for the antenna could be designed, and the forces acting on the towing mechanism where it connects to the antenna and the vehicle could be performed. This approach would allow a towing mechanism to be built that would be durable enough to tow the heavy antenna over rough terrain, and also one that would react better during the times that the rover is turning.

The simulation could be extended to test the performance of the vehicle. For example, snow buildup can cause the antenna to become partially buried and to increase the weight of the antenna significantly. More testing could be done to determine how much force is needed initially to get a weighted antenna to move. This could also affect how long the vehicle is allowed to pull the antenna in conditions with blowing snow before the vehicle must return to a location where the antenna can be cleaned off. If there is a lot of blowing snow, then there is a possibility that the vehicle may not be able start moving if it stops, or the added weight could cause the vehicle to stop and become stuck.

Another area that can be extended in the simulation is the antenna. Currently, the antenna is modeled as a large square object completely dragging on the ground. Improving how the antenna rides on the ground could result in the greatest improvement in terms of mobility for the vehicle. This is limited by the radar team, however, as it is most desirable that the antenna lay completely flat on the ground to receive the best quality signal. This and other possible additional work can enhance the quality of the model and eventually result in the design and building of better robots for polar regions. The enclosure may have to be changed, however, depending on the weight and size of the new vehicle. If the scientific payload increases much in size, then the enclosure may have to be reduced. The enclosure could be removed completely if the size of the equipment becomes too large. In this case, separate structures could be built specifically to carry the equipment. The model could then be used to determine the best location to for the structures.

If it is decided to use a new vehicle for the robot base, then new models can be created and tested again, comparing the results with the first version. If building a new base, then the old model can be used as a starting point, attempting to keep all the advantages of the old base while improving on other parts of the vehicle. For instance, more space could be allocated to the enclosure while also reducing the center of gravity and increasing the ground clearance.

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