DESIGN AND DEVELOPMENT OF A THREE DIMENSIONAL KINEMATIC SIMULATION, STEERING SYSTEM AND SCIENTIFIC INSTRUMENT DEPLOYMENT MECHANISM FOR A PLANETARY MICRO-ROVER

by
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ABSTRACT

Three separate topics in the design of a planetary micro-rover have been investigated including the design and development of: a three dimensional kinematic simulation, a steering system, a scientific instrument deployment mechanism. The simulation models rover motion and sensor readings as the rover travels over various terrain. The simulation is used in the evaluation of the rover's hazard avoidance software. The steering system investigation explores three different types of steering for a rover with conical shaped wheels. These three types of steering include tank steering, steering using wheel speeds, and a hybrid steering system which uses a worm gear as a locking mechanism. A two degree of freedom deployment mechanism as been designed and built to deploy a scientific instrument from the rover. This design investigates different compliance techniques to improve instrument positioning in an unknown environment.

Technical Supervisor: Dr. David S. Kang

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Shane M. Farritor

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CHAPTER 1

1.1 MOTIVATION

It has been twenty-five years since American astronauts first walked on the moon. Twelve Americans spent a total of 300 hours on the surface of the moon. Then in 1972, with the launch of Apollo 17, manned lunar exploration came to a halt.

There is no doubt that one day, in the near future, man will again explore the surface of our moon, the surface of other planets, and other moons. However, this will not occur before more is known about these distant places.

Today there is a different outlook on programs such as Apollo. Tight economic constraints make such large expenditures of money difficult. Increasingly NASA and other science organizations, are moving toward smaller, less expensive missions. These smaller missions must be very efficient, providing sizable scientific return per dollar spent. The use of robotic explorers can be an inexpensive and efficient way to gather scientific information about our universe.

Robotic space exploration versus manned exploration of space has been debated since the beginning of the space program. Each route has definite advantages as well as disadvantages. The tremendous success of robotic probes such as Viking, Voyager, and Magellan have shown that such missions can provide a wealth of information. However, robotic exploration has its limitations, robots cannot perform many of the tasks that can only be accomplished by humans.

The desire to return to the moon and then on to Mars is present. This was expressed in a speech made by President Bush on July 20, 1989, the twentieth anniversary of the launch of Apollo 11. President Bush called for the development of a major space station, the return to the moon for permanent manned presence, and a manned mission to Mars [13].

To help accomplish these goals, within tight economic constraints, NASA has proposed the use of smaller, faster and cheaper missions. These missions will gather the knowledge required for such an ambitions exploration initiative.

The Mars Environmental Survey (MESUR) program is designed to increase our knowledge of the planet Mars. This program includes a precursor mission called MESUR Pathfinder. The purpose of the Pathfinder mission is to demonstrate Mars entry and landing technology as well as the use of a micro-rover for exploration. Following this will be larger missions to set up 8 to 16 science stations on the surface of Mars.

These stations will study meteorological and seismic activity for two Martian years (approximately four earth years). The effectiveness of these stations will be augmented by the use of a micro-rover. A micro-rover is a small vehicle which will extend the reach of each station by exploring the surrounding area and transporting scientific instruments [15].

1.2 ROVERS AND MICRO-ROVERS

Rovers are vehicles that can be used to explore the surface of a planet. Rovers have been used by both the United States and the Soviet Union in the exploration of the moon. These rovers have been manned and unmanned.

The United States launched a rover with the Apollo 15, 16, and 17 missions. This lunar rover was a four wheeled vehicle designed to transport two astronauts. These rovers could traverse large distances and it greatly increased the area that could be explored by astronauts.

In 1970 the Soviet Union also landed a roving vehicle on the moon. This rover was an unmanned vehicle used to gather scientific data. It operated for 220 earth days (7 lunar days). The Soviet Union controlled their rover from a station on earth. This method or robotic control is called tele-operation. This rover was followed by another successful rover mission in 1973.

A planetary rover must be highly mobile to traverse the unknown surface of another planet. The rover must be capable of transporting payload to various locations across the surface. This payload may be in the form of astronauts or scientific instruments.

The recent miniaturization of electronic and mechanical devices makes the use micro-rovers possible. A micro-rover is a smaller vehicle weighing approximately 20 pounds (10 kg). Because of the micro-rover's small size transportation cost to the planetary surface is greatly reduced. This makes it possible to launch a small army of these vehicles to explore many diverse locations across the surface of a planet. A large number of independent rovers greatly increase the probability of a successful mission.

1.3 MISSION REQUIREMENTS

1.3.1 Goals

A rover would be carried to the surface within a stationary landing craft. This craft, referred to as a lander, will most likely be the communications link between the rover and earth. Various mission scenarios call for rovers to operate tethered to the lander or as stand alone systems. The rover would receive high level mission commands from the ground crew on earth, while being required to make low level decisions on its own. For instance, the rover would be given a destination from the ground crew, then would be required to reach that destination on its own. Once the rover has arrived at it's destination it would transmit a video image to earth and perform scientific experiments. After this work is complete the rover would shut down for the day and recharge its batteries.

This video image would then be examined by the ground crew. A place of interest in the photograph would be chosen as the next destination. This ground image could be combined with a rover simulation to test the rovers ability to reach this destination. Then this new destination, along with hints on how to get there, could be sent to the rover for the next day's mission.

The current concept calls for a thirty day mission, with the rover traveling 100 yards (100m) per day. Each day the rover will transmit 2 video images [4].

1.3.2 Environments

For a rover to complete its task, it must be capable of surviving in the harsh environment of another planet. The rover will also be subjected to the harsh environments of launch from earth and transport to that planet.

During launch the rover will experience excessive vibrations from the rocket engines as well as static loads from its acceleration into space. Once in space the rover will experience temperature extremes, a vacuum, and intense radiation. When the rover arrives at its destination it must survive the loads experienced as it lands on the surface of the planet (impact loads estimate is 50g).

Once on the Surface of Mars, the rover will be subjected to more temperature extremes. Temperatures vary from -193°F (-125°C) to 71°F (22°C). Mars's atmosphere is primarily carbon dioxide and a much lower density as compared to earth's atmosphere. The pressure of the Martian atmosphere is approximately 1% of earth's. Severe winds are common on the Martian surface, winds at the Viking landings sights reached 55 miles per hour (90 kph). These high winds, coupled with the fine Martian soil, make resistance to fine dust a necessity.

The lunar surface is a bit different than the surface of Mars, primarily because the moon lacks an atmosphere. The lunar terrain is much less rocky than the Martian surface but it is covered with a fine dust and many craters of all sizes.

1.4 THESIS SCOPE

This thesis describes work done to advance the development of a planetary rover, called MITy. MITy is designed to explore either the surface of the Moon or Mars.

In chapter two, previous work on the MITy series of rovers is described. Chapter three discusses work done on a three dimensional kinematic simulation used to test and evaluate the performance of the rover design and hazard avoidance ability. Chapter four describes the design and evaluation of the third prototype rover. Then, chapter five discusses the design and development of a mechanism to deploy scientific instruments from the rover. Finally, a summary of the conclusions drawn from this work can be found in chapter six.

Some work described in chapter three and four was conducted with the aid of other rover team members. In section 3.4 the simulation animation software was coded by Kimbal Thurston. Also, modifications to the rover hazard avoidance software discussed in section 3.5.1 was done in cooperation with Eric Mallefew. Electronic work associated with the construction of MITy-3 was done by Sean Adam. The Author was aided in the mechanical construction of MITy-3. Giang Lam designed and built the conical wheels and instrument box frame and Bill Kaliardos helped in the construction of the steering system. Special thanks goes out to these team members for their contributions to this thesis.

THE MITY ROVERS
CHAPTER 2

2.1 THE MITY SERIES

The MITy rover series has been developed at the Charles Stark Draper Laboratory in conjunction with the Massachusetts Institute of Technology. Development of the MITy rovers has been undertaken as a student project. This Project began in the fall of 1990 with an initial systems study completed in June 1992 [4]. To date, three prototype rovers have been built: MITy-1, MITy-2, and MITy-3. Development of both MITy-1 and MITy-2 has been completed, while construction of MITy-3 continues.

While teleoperation of a rover on the moon is possible, the long communications delay between earth and other planets (up to 40 minutes) makes teleoperation impractical. For this reason the design of the MITy rovers has concentrated on a high degree of autonomy. Each of the three prototype rovers are completely self-contained units carrying with it its own power supply, processor, and sensors.

In order to complete its mission a rover must be capable of finding its way through an unknown environment. To accomplish this task, the rover must be able to sense its environment, detect problem areas, and avoid them. The rover must also know where it is, where it has been, and where it is going at all times. To accomplish this the MITy rovers are equipped with a complete navigation and hazard avoidance sensor package.

2.1.1 Basic MITy structure

Structure

Each rover is based upon an articulated three platform frame. Two wheels extend from the sides of each of the three platforms. Motors within each wheel provide actuation. Connecting the individual platforms are two flexible steel rods. These flexible rods allow relative motion between the platforms in both pitch and roll rotations, but not yaw. The basic rover structure is illustrated in figure 2.1.

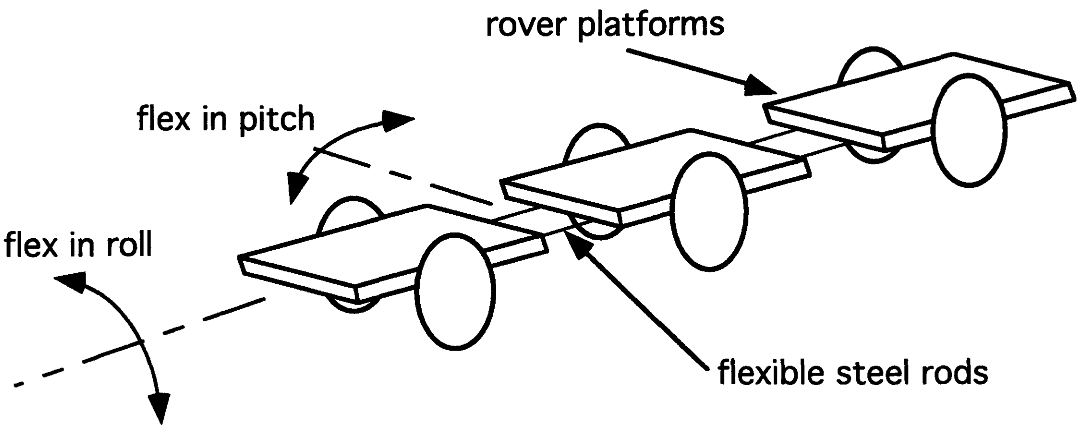


Figure 2.1: Basic MITy Structure

Since the rover spends most of its time moving forward, the front platform is dedicated to hazard avoidance sensors. The front platform is also home to the video camera as well as the video and data transmitters. Within the center platform is the main processor and power regulation circuitry. Navigation sensors are also primarily located on the center rover platform. The rear platform carries the rover battery power supply as well as the recharging solar array. Space on the rear platform has been reserved for scientific instruments.

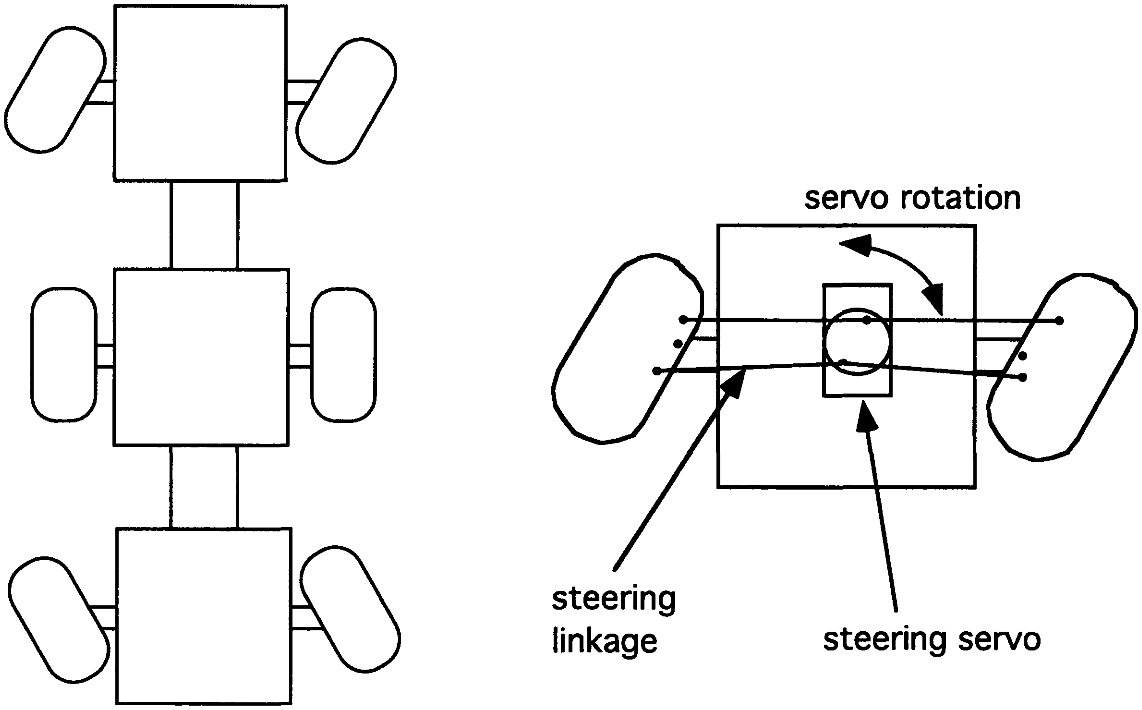
Locomotion

As the rover traverses rough terrain the flexible frame of the rover will adapt and conform to the terrain beneath it. This helps redistribute the weight of the rover, and guarantees good contact between each wheel and the ground. The use of six wheels, as opposed to four, helps ensure sufficient wheel-ground traction. Using six individually powered wheels maximizes the number of wheels in contact with the ground. If one or two wheels would happen to loose traction, for whatever reason, the other wheels will still provide traction. Also, with six individually powered wheels, the system becomes more resilient to a motor failure and therefore much more reliable.

Steering

MITy-1 and MITy-2

Rover steering is accomplished by rotating the front and rear wheel pairs while the middle platform wheels remain fixed. A rover right turn is shown in figure 2.2a. MITy-1 and MITy-2 utilize an Ackerman steering system similar to that used on automobiles. On these rovers the front and rear wheels are allowed to pivot about a point near each wheel's contact point, reducing the torque required to turn them. Wheel steering is actuated by a servo motor located on the front and rear platforms. This steering servo is connected to the wheels by a linkage as shown in figure 2.2b.



a) Rover Right Turn
Top View

b) MITy-1 and MITy-2 Steering

Figure 2.2: MITy-1 and MITy-2 Steering

This linkage, along with the servo motor geometry, gives the rovers a fixed minimum turning radius. MITy-1 has a 24" turning radius while MITy-2 has a 19" turning radius. This turning radius is a limitation that must be accounted for in planning the motion of the vehicle.

Power

Electrical power on a MITy rovers is provided by rechargeable nickel-cadmium batteries. MITy-1 carries a total of 54 watt-hours on board while MITy-2 and MITy-3 each carry 24 watt-hours. MITy-2 is also equipped with a solar panel to restore on board power. The current solar panel charges at a rate of six watts.

Processing

Processing for MITy-1 is provided by a Motorola 68HC11 processor. This is a 2 MHz micro-computer with 32 kbytes of memory.

MITy-2 and MITy-3 utilize a ZILOG Z-180 micro-processor. This is a more powerful processor then implemented on MITy-1. The Z-180 processor is a 12 MHz processor with 256 kbytes of memory. MITy-3 has a memory expansion to 512 kbytes.

Processor performance is a major concern since the processor is responsible for all aspects of rover operation. Obviously sophisticated sensors and sophisticated hazard avoidance planning place a great demand on the rover's processor. There are also strict size and power restrictions placed on the processor.

Vision

Both MITy-1 and MITy-2 are equipped with on board video cameras. These cameras are used to gain information about the rover's surroundings. Obtaining this picture information would be a primary goal of a planetary rover's mission. Currently the video information is merely transmitted to the ground station and is not used by the rover itself. Work is in progress to utilize this video in navigation and hazard avoidance. For more information on this work see [6].

2.1.2 MITy-1

MITy-1 was a proof-of-concept platform. The intention of this rover was to show that a vehicle could be built that would satisfy the basic mission requirements such as size, weight, cost and vehicle performance. A picture of this rover can be seen in Figure 2.3.

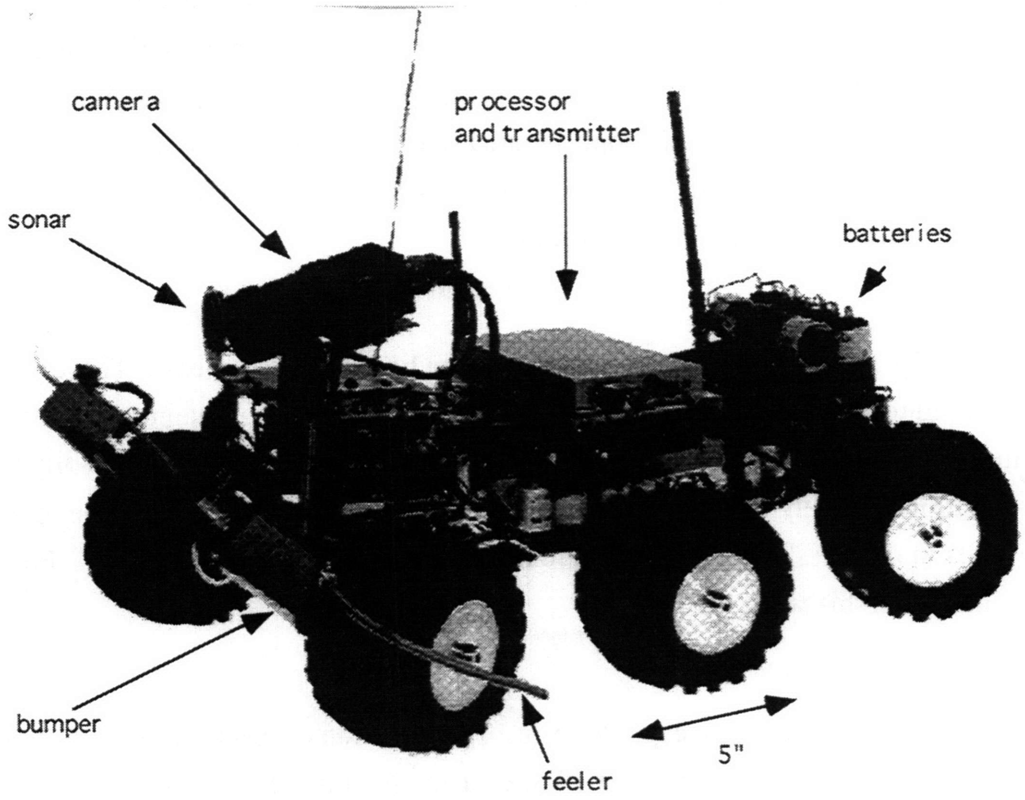


Figure 2.3: MITy-1

Platform

MITy-1 is the smallest of the three MITy rovers. MITy-1 is 26" long and 13.4" wide weighing approximately 20 lbs. (8.9 kg).

MITy-1's locomotion is provided by six IM-13 globe motors. These motors are accompanied by a spur gear head with a speed reduction ratio of 96:1. After gearing these motor's theoretical stall torque is 327 oz.-in (2.314 N-m). This allows the rover to climb a 3.75" step consistently, approximately 75% wheel height.

Sensors

Sensors implemented on MITy-1 are not realistic sensors for use in a planetary mission. Since MITy-1 was a proof of concept vehicle, sensors were chosen on the basis of cost and simplicity, rather than actual mission performance.

Navigation

MITy-1 uses a drag wheel to measure distance traveled. A drag wheel is an unpowered wheel that is pulled behind a rover platform. An unpowered wheel provides better distance information than a powered wheel because it is less susceptible to slip. Drag wheel rotation is measured by an optical encoder from which rover travel distance can be calculated.

A magnetometer is used on MITy-1 to determine vehicle heading. This heading information, coupled with vehicle travel, allows the rover to determine its position relative to where it began.

This method of indirectly determining location is called dead reakoning. In dead reakoning, motion information such as wheel speed and heading are integrated to estimate vehicle position.

Hazard Avoidance

Since the rover is traveling through an unknown environment it must be capable of detecting hazards and avoiding them.

For this purpose, MITy-1's primary source of information is three sonar sensors. These sonars are mounted on the front of the vehicle and provide distance information on objects in front of the rover. The sonars are sensitive to objects in a 24° beam width. The combination of the three sonars gives MITy-1 a 60° field of view with slight gaps.

MITy-1 utilizes feelers to detect its local environment. Feelers are rods that extend from the front edges of the MITy-1 platform. If MITy-1 passes an obstacle too closely the feeler will deflect. The amount of deflection determines the distance to that obstacle.

As a last line of defense MITy-1 has bumpers on the front of the vehicle. If the rover runs into an obstacle, the bumper will be depressed, and a switch will be activated. The bumper is placed above the rover's maximum climbing height.

Vehicle Control Software

MITy-1 is capable of autonomous travel through hazardous terrain. If the rover is given a target with respect to its initial position, it will then drive toward that target while reacting to and avoiding obstacles.

MITy-1 has a purely reactive hazard avoidance scheme. This is to say that the rover does not plan ahead, but merely reacts to the situation in which it is placed. Sonar, feeler and bumper information is integrated to determine the best direction for the rover to travel. Decisions are made based on this sensor information and subgoals are placed to help lead the rover to its destination [1].

All decisions are made based on the assumption that the rover is operating in a two dimensional environment. Tilting of the vehicle due to rough terrain or hills and valleys is not considered in the MITy-1 vehicle control algorithm.

2.1.3 MITy-2

MITy-2 was the next stage in MITy rover development. It was a big step beyond MITy-1 both mechanically and electrically. The primary goal of MITy-2 was to develop a more mission-ready rover. Mechanical structure, sensor package and software all were upgraded. A photograph of MITy-2 can be seen in figure 2.4.

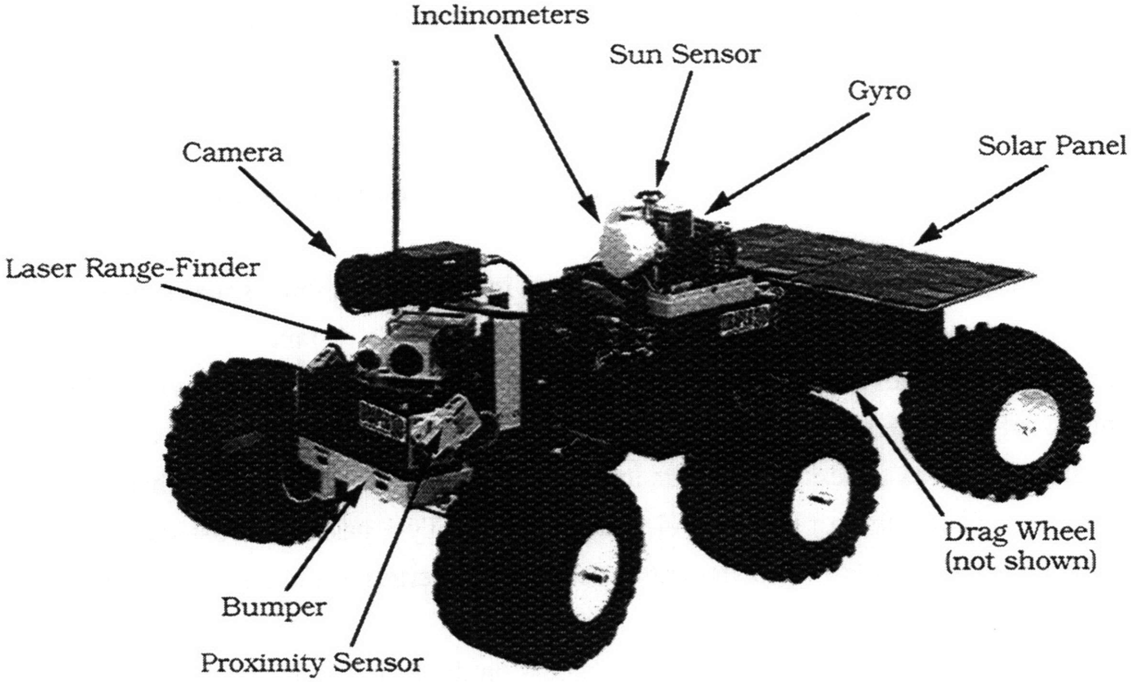


Figure 2.4: MITy-2

Platform

The platform for MITy-2 is very similar to the first prototype rover. MITy-2 is larger than MITy-1 because additional space was required to house added sensors and equipment. MITy-2 is 29” long and 18” wide. MITy-2 also utilizes more powerful drive motors than MITy-1 to increase vehicle mobility. MITy-2 uses Micro Mo 2842 DC motors with a planetary gear reduction of 134:1. These motors have a theoretical stall torque of 924 oz-in (6.53 Nm) after gearing. The gear head efficiency is estimated to be 60%. These motors are also equipped with tachometers.

Sensors

The goal of MITy-2 was to implement a more mission ready sensor package while keeping performance high and costs low. The MITy-2 rover also includes redundancy in sensors wherever possible to increase reliability. For more information on MITy-1 and MITy-2 sensor systems see [2].

Navigation

For odometery, MITy-2 uses both an unpowered drag wheel and motor tachometers. The use of two independent systems increases reliability and accuracy. On flat ground the drag wheel provides more accurate distance data. This is because the drag wheel is unpowered and not as susceptible to wheel slip. Conversely, in rough terrain the drag wheel has a tendency to loose contact with the ground surface and the tachometers provide more reliable information.

MITy-2 uses a sun sensor and a gyroscope to ascertain vehicle heading. Both sensors are mounted on the center platform. The gyroscope measures the angular velocity of the vehicle. This information is then integrated to determine angular displacement. Over time, the gyroscope is susceptible to drift; therefore, it is used as the secondary system. The sun sensor is used to calibrate the gyroscope and is the primary sensor used to determine vehicle heading. The sun sensor uses a fish-eye lens to project light from the sun onto a position sensitive detector. This information, coupled with inclinometer readings, the time of day and geographic location determine vehicle heading. The sun sensor is used if a strong signal is received, if this signal is weak or lost the gyroscope becomes the primary heading sensor.

The center platform is equipped with inclinometers to determine it's pitch and roll. These inclinometers are used to avoid situations in which the vehicle might tip over. Readings from these inclinometers also allow for three dimensional navigation.

Hazard Avoidance

The primary hazard avoidance sensor on MITy-2 is a laser range finder. This range finder is mounted on the front platform. The range finder utilizes a triangulation method to provide distance information on obstacles from zero to ten feet. This range finder is mounted to a rotating turn table to give 180° of coverage in front of the vehicle.

MITy-2 utilizes two optical proximity sensors on the front platform to detect crevasses and drop-offs. These sensors are pointed downward in front of the vehicle to determine if the surface ahead of the vehicle is traversable.

The front platform is also equipped with accelerometers to determine the pitch and roll of the front platform. This information is needed to ensure the reliability of other sensors located on this platform such as the laser range finder and proximity sensors.

As a last line of defense, MITy-2 is equipped with bump sensor on both the front and rear platforms. These sensors determine if the rover has contacted an obstacle.

Vehicle Control Software

Hazard Avoidance Software

MITy-2 is able to autonomously navigate hazardous terrain in order to reach a target destination. The rover is in contact with a ground station at all times to report information on its progress and provide real time video images.

MITy-2 utilizes an effective algorithm which allows the rover to navigate difficult situations while maintaining a maximum degree of vehicle safety. This algorithm, like the MITy-1 control algorithm, is a reactive scheme. The primary sensor information for hazard avoidance comes in the form of distance measurements obtained by the laser range finder. As the range finder sweeps ahead of the vehicle, as in figure 2.5 a), the rover builds a local map of the surrounding terrain. Obstacles in this map appear as shorter distance readings and this is plotted against angular position of the obstacles. A sample map is shown in figure 2.5 b).

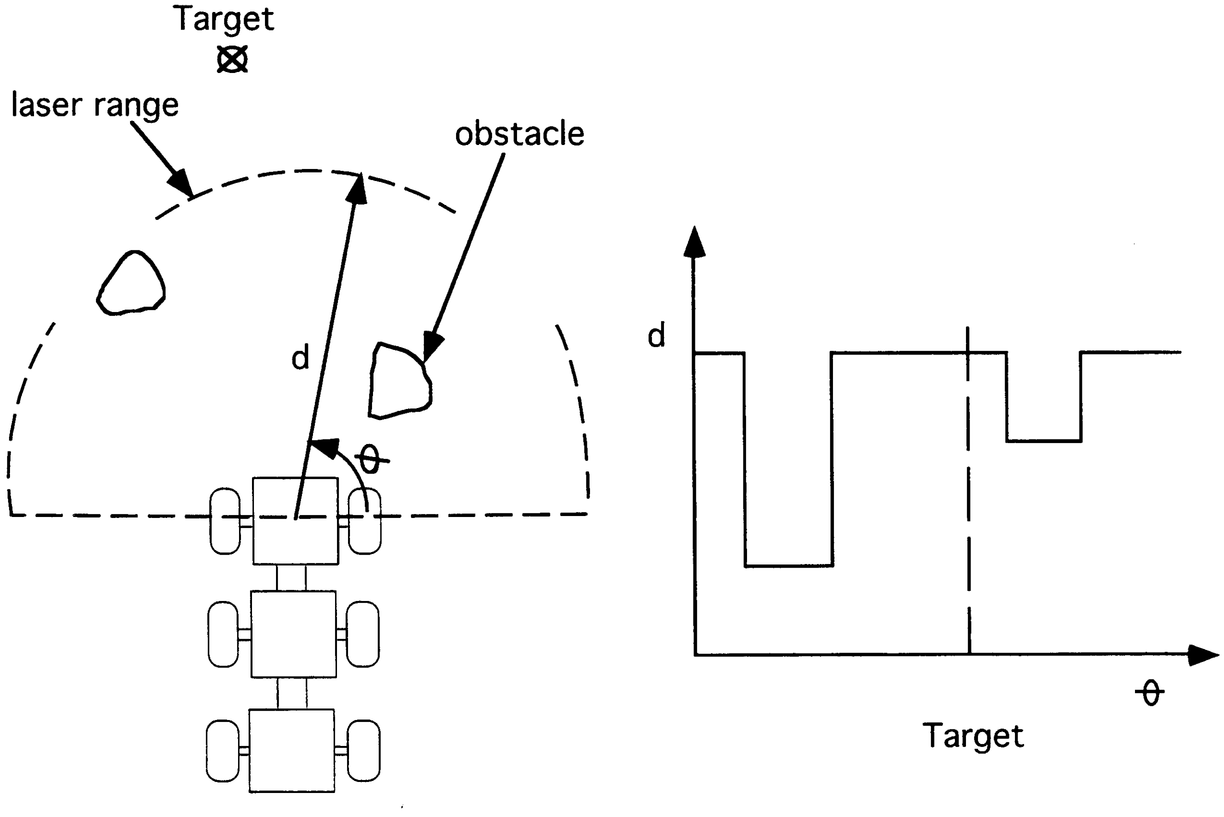
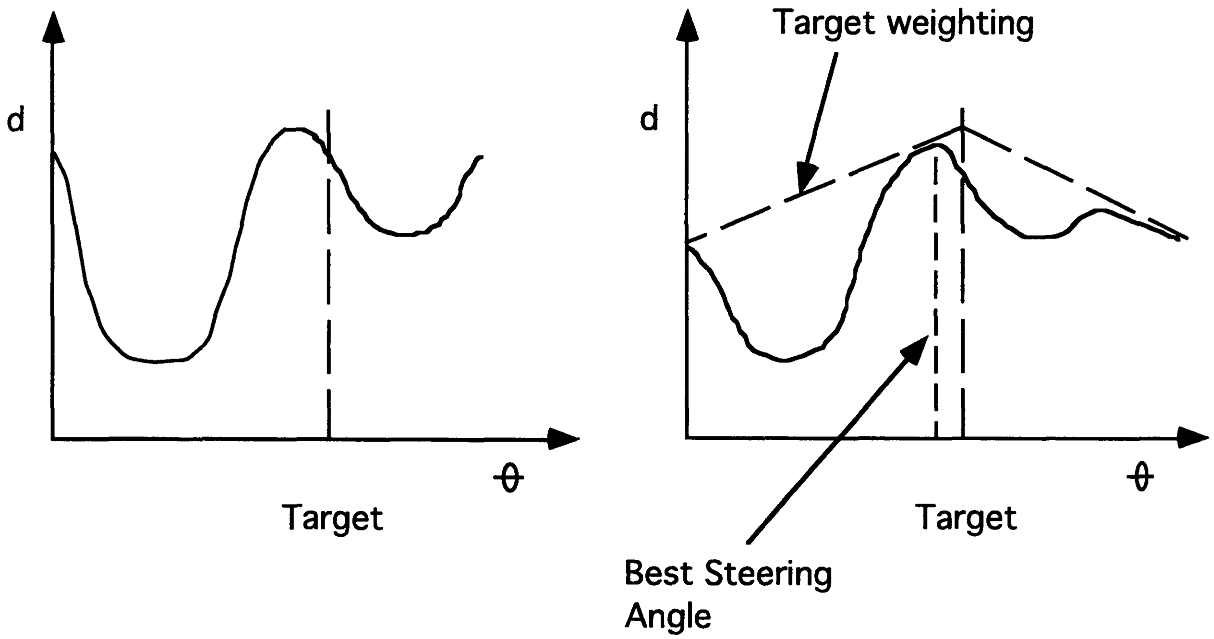


Figure 2.5: Basic Obstacle Map

Tracking and sensor errors make it is unsafe to pass too closely to an obstacle. For this reason, the obstacle map is adjusted to account for the rover turning radius as well as this passing safety distance to the obstacles, an example of this is seen in figure 2.6 a). This part of the routine balances the trade-off between the travel distance and passing safety while incorporating the vehicle turning radius.

Finally the map is weighted to include the target location and past motion of the rover, as seen in figure 2.6 b). This is to ensure the rover will travel toward the target while avoiding obstacles and will not oscillate left and right on its way.



a) map weighted for safety b) map weighted for target location

Figure 2.6: Weighted Maps

This planning algorithm also assumes that the rover is operating in a planar environment. Considerations such as hills, valleys, drop-offs, and rock climbing are not directly considered. Therefore, rover performance is severely degraded when these three dimensional effects are present. Work to alleviate this problem is presented in chapter three of this thesis. Additional information on this work is available in [1].

Ground Station

To aid in the operation of the rover a full ground station has been developed. This ground station enables the user to control the rover via a radio link. The ground station sends commands to the rover and sensor information from the rover is returned to the ground station. This is accomplished through a graphical interface on the ground station computer. The ground station allows the user to know exactly what the rover is "thinking" at all times, so the rover can be monitored or controlled. The user can then teleoperate the rover. With the information gained by the rovers sensors, the user can make decisions for the rover and send commands for the rover to act. With the benefit of a "man-in-the-loop" the rover performance can be greatly enhanced.

This teleoperation can be done on a low or high level. Teleoperation on a low level amounts to sending the rover speed and steering commands. In this situation, the rover's safety mechanisms are still in effect to protect the rover. These safety mechanisms include the bump sensors and proximity sensors. In a higher level interaction the rover can be lead to its destination by the placement of subgoals, allowing the rover to decide how to achieve each subgoal. The coding of the ground station was done by rover team member Matt Ferdette.

2.1.4 Future of MITy Series

With the tremendous success of the first two prototype rovers, work was begun on a third prototype. This rover, MITy-3, is currently under construction and much of this work is included in the fourth chapter of this thesis.

Problems with vehicle mobility are addressed with this third prototype rover. Conical wheels are utilized to increase vehicle mobility and prevent the rover from becoming "high-centered" on obstacles. With the use of conical wheels came the need for a new steering system.

With future prototypes other problems will need to be investigated. The brunt of these problems are associated with the space environment the rover will experience. This includes things such as extreme temperature variation, severe dust, launch vibrations, radiation and the vacuum of space.

2.2 OTHER ROVERS

Micro-rover design is not unique to the MITy series. Development of planetary rovers has been undertaken by teams at the Jet Propulsion Laboratory, Russian Space Agency, Martin Marietta and Sandia National Laboratory. The most advanced planetary rovers have been developed by JPL and the Russian Agency.

2.2.1 JPL's Rocky

The Jet Propulsion Laboratory (JPL) has been working on development of planetary rovers for many years. JPL is now working on a series of rovers called Rocky.

Rocky is roughly equal in size to MITy-2. The Rocky series will culminate in 1996 with the flight of a vehicle to Mars in the MESUR/Pathfinder mission. Additional rovers will be launched on later MESUR missions.

JPL's design philosophy has differed from the MITy series in that JPL is creating a space qualified rover. Due to budget constraints this is not yet possible with the MITy program.

Rocky, like the MITy rovers, is a six wheeled vehicle with an articulated frame construction. Rocky's six wheels are individually powered by motors mounted within the wheel. Steering is accomplished by individual steering motors which rotate the four corner wheels. The steering motors pivot these four wheels about the point of contact between the wheel and the ground minimizing tire scrub. JPL also utilizes a discretely articulated flexible frame to increase vehicle mobility. Rocky's frame is hinged to allow the structure to adapt to the ground profile. This arrangement allows Rocky to turn in place and climb vertical steps somewhat higher than its 5.12" (130mm) wheel height. The ground clearance of the rover's main body is slightly higher than this climbing height limit. Although the area beneath the rover is higher than the rover's maximum climbing height, this is still a space where the rover can become high centered and stuck.

For hazard avoidance, Rocky is equipped with two laser range finders and mechanical contact sensors. The range finders flash a strip of light across the ground profile. This signal is detected by a CCD and then distance readings are obtained using triangulation.

JPL uses stereoscopic video images from the lander and the rover to plan Rocky's path. The rover then follows this path sent from the ground crew. The rover does this using on board software and dead reakoning. For navigation the rover uses a sensors such as a gyroscope, inclinometers, and wheel rotation counters. [19]

2.2.2 Russian Rover

The Russian Space Agency is also producing a rover for planetary exploration. The Russian rover, called Marsokhod, is a bit larger than the MITy series rovers. This rover is approximately 4' (1.2m) in length and 3.25' (1m) in width and weighs 175 pounds (75 kg).

Marsokhod also uses an articulated frame with six individually powered drive wheels. The frame connecting the three sections is hinged and these joints are powered so they can be moved or locked in place. This allows the rover to cross small crevasses. Marsokhod is equipped with a radio isotopic thermal generator (RTG) which provides rover power. This system produces an abundance of electrical power and thermal energy. The Russian rover utilizes conical wheels as used on MITy-3.

The Russian Space Agency plans a 1996 mission to Mars that will deploy two planetary rovers and a balloon to explore the surface.

THREE DIMENSIONAL ROVER SIMULATION
CHAPTER 3

3.1 MOTIVATION

3.1.1 Hazard Avoidance Testing

The most challenging aspects of autonomous navigation rise from the lack of detailed information about the environment to be navigated. The problem is further complicated by the uncertain location of the vehicle within that environment. Both of these difficulties are amplified when the problem is considered in three dimensions.

In a two dimensional situation the rover position can be defined by an {x,y} location of the rover along with the rover rotation. Obstacles can be located by determining their {x,y} location with respect to the rover. In a two dimensional navigation problem an area is either a passable space or an obstacle. If the locations of the rover and the obstacles can be determined, autonomous navigation can be attempted, although this task in itself is by no means trivial.

In a three dimensional scenario the task becomes even more difficult. The rover position must now be defined by at least six variables, three translational and three rotational. In the case of a multi-bodied vehicle, such as the MITy rovers, more variables are required. The definition of an obstacle is also less clear in a three dimensional representation. Obstacles are no longer simply passable or impassable. Some obstacles may be surmounted while others must be avoided. The definition of an obstacle becomes more complicated including such things as hills and cliffs.

The physical construction of the vehicle is very important in a three dimensional problem. This will determine what obstacles will hinder rover movement and what obstacles the rover can climb. The location of the sensors and actuators can also be adversely affected by three dimensional terrain, therefore their performance may be degraded. For instance as the vehicle climbs a rock the laser range finder will not be in its normal operating position, it may be pointing toward the sky or directly at the ground, and therefore cannot be relied upon.

All of these problems must be considered in the design of a successful hazard avoidance system. Previously, a two dimensional simulation was used to design and evaluate the hazard avoidance system developed for the MITy rovers [1]. Now this work must be built upon by the evaluation of the hazard avoidance routine in more complicated and more realistic terrain. To accomplish this, a simulation has been developed to subject the hazard avoidance system to more realistic situations.

3.1.2 Aid to Rover Operations

A three dimensional simulation can be of great use during actual rover operations. At the end of each day the rover will transmit a video image to the ground crew before it shuts down for the night. This video image will most likely be stereoscopic, therefore, the ground crew can use this information to reconstruct a three dimensional map of the area ahead of the rover. Once this ground profile is constructed it can be used by a rover simulation. This would allow the ground crew to evaluate the rovers likelihood of arriving at its next destination. If problem areas are found the rover can be advised to avoid these areas before it gets into trouble. By identifying problems and avoiding them ahead of time, the rovers performance and reliability will be greatly enhanced. With this help the rover will be less likely to waste time and energy trying to get through areas that are impassable.

This reconstructed map will not be perfectly reliable and the rover will have do much of the work on its own, but the use of multiple simulation runs will increase the certainty of mission success.

3.1.3 Rover Teleoperation Testing

Another use for a three dimensional simulation is in the design and evaluation of a user operating station, or ground station, for the rover.

Work is currently in progress to operate the simulation in conjunction with the existing ground station software. Since the same rover control software is used with the simulation as is used on the actual rover, the ground station can interact with the simulated rover in the same way it would with the actual rover. The rover control software is really blind to the environment, in other words the control software cannot tell if it is controlling the simulation or the actual rover. This leads to the fact that the rover can be teleoperated in the simulation in the same way as it would be in reality. Now, the simulation can be used to evaluate the user interface and the ground station, i.e. it can be used as a ground station development tool. In this manner the simulation could also be used to train a rover teleoperator.

3.1.4 Sensor Evaluation

Still another use of the simulation would be in the evaluation of proposed sensors. Proposed sensors could be modeled and incorporated into the simulation environment. Once incorporated, the simulated rover could be operated in various terrain and the effectiveness of this new sensor could be evaluated. The use of the simulation in this manner would reduce the cost and time required to evaluate a new sensor system.

3.2 SIMULATION STRUCTURE

The evaluation of the hazard avoidance system in a three dimensional environment was the major purpose for which this simulation environment was developed. Therefore, the level of complexity of the simulation was limited by this complexity's contribution to hazard avoidance evaluation. The complete simulation was separated into two distinct parts: the control system and the environment. The newly developed three dimensional environment has been incorporated with the existing control code to evaluate this control systems performance. Then the results of this merger were used to improve the control system by making it more functional under more realistic conditions.

3.2.1 Kinematic Simulation

In the simulation environment the rover and the ground profile are modeled kinematically. The shape of the ground profile is specified, then the rover is placed on this ground profile. The shape of the rover is completely determined by how it interacts with, or "rests on", the ground profile. Then the motion of the rover is integrated and its position advanced. No mechanical dynamic effects are considered in the motion of the rover, this ignores things such as bouncing, vibrating or other dynamic effects. Furthermore, no dynamics are considered in the rover interaction with the ground profile. This neglects thing such as soil conditions, wheel slip and rover sliding. These effects are considered in a previously developed hi-fidelity simulation that focused on these issues in great detail [3]. The results of this dynamic simulation are used as operational limits for the simulation. For instance, the dynamic simulation placed limits on the maximum slope the rover could climb, and this slope was noted in kinematic simulation development. It was thought that the consideration of dynamic effects would bog down and not be relevant to the goal of the simulation.

3.2.2 Simulation Coordinate Frames

The simulation environment consists of the model of the rover itself as well as the model of the ground profile. The simulation environment is defined by two major coordinate frames. One coordinate frame is an inertial frame fixed with respect to the ground profile. The second is a moving frame that is fixed with respect to the center platform of the rover. The moving frame is referred to as the rover frame and the fixed frame as the ground frame. The origin of this rover frame is placed below the center platform at the midpoint between the contact of the center platform wheels with the ground. The {x} axis of this frame is parallel to the length of the rover with the positive direction forward. The {z} axis is oriented directly upward and the {y} axis is oriented to form a right handed frame. These frames are shown in figure 3.1.

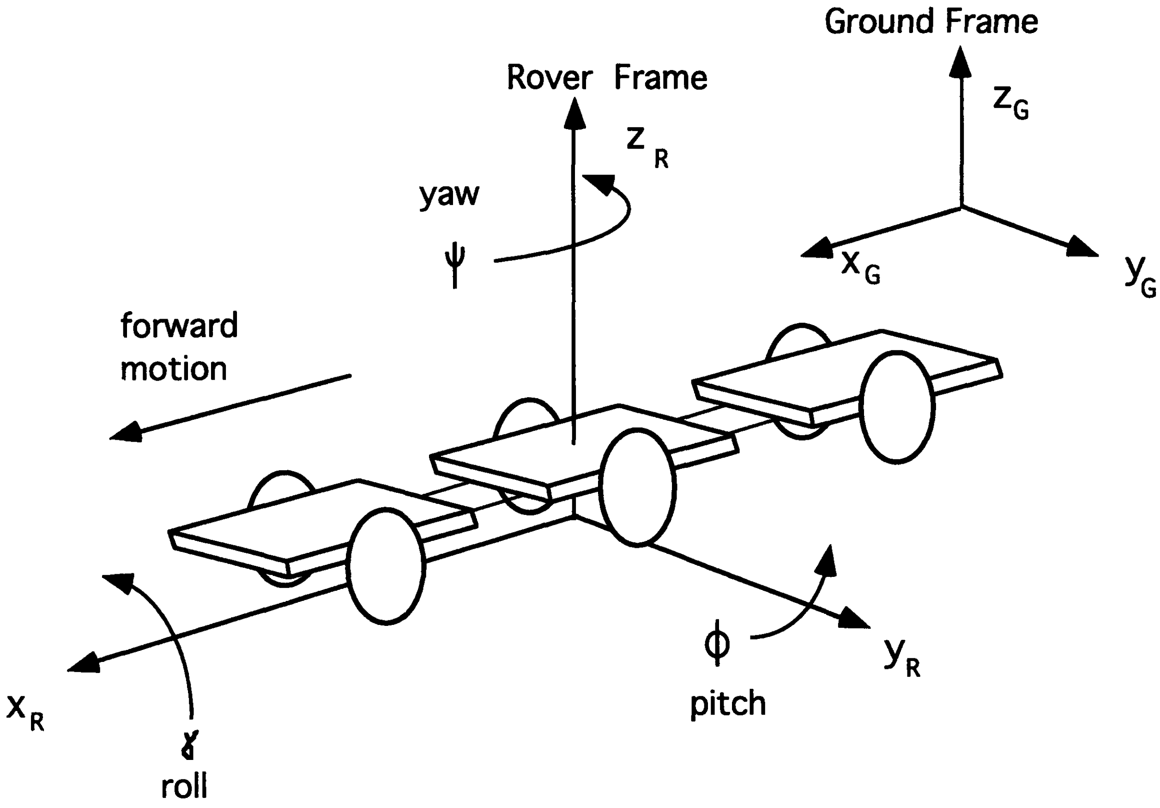


Figure 3.1: Simulation Coordinate Frames

A transformation was used throughout the simulation to relate the two frames. The rotations of these two frames with respect to one another is determined by the roll (γ), pitch (ϕ), and yaw (ψ) of the center platform. The displacement of the origin of the rover frame with respect to the moving frame is defined by the {x,y,z} position of the rover.

A vector in the rover frame can be represented in the ground frame by the following transformation:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_G = \begin{bmatrix} \cos\phi\cos\psi - \sin\phi\sin\gamma\sin\psi & -\sin\psi\cos\gamma & \sin\phi\cos\psi + \cos\phi\sin\gamma\sin\psi \\ \cos\phi\sin\psi + \sin\gamma\sin\phi\cos\psi & \cos\gamma\cos\psi & \sin\phi\sin\psi - \sin\gamma\cos\phi\cos\psi \\ -\sin\phi\cos\gamma & \sin\gamma & \cos\gamma\cos\phi \end{bmatrix} \begin{bmatrix} x \\ y \\ x \end{bmatrix}_R + \begin{bmatrix} r_x \\ r_y \\ r_z \end{bmatrix}_G$$

(equation 3.1)

Where $\{x,y,z\}_G$ is a vector in the ground frame, $\{x,y,z\}_R$ is a vector in the rover frame, $\{r_x,r_y,r_z\}_G$ is the displacement of the origin of the rover frame in the ground frame, and ϕ, γ, ψ are the pitch, roll and yaw of the rover frame, respectively. Since the roll and pitch of the vehicle are expected to take on relatively small rotations while the yaw can take on any value, the order of rotation is yaw then roll then pitch. With the singularity in velocity occurring when roll takes on values of $n\pi/2$.

3.2.3 Simulation Variables

In the simulated environment the rover is represented by a geometric model. The position of the model is determined by a ten element state vector. The first six elements of this vector contain the $\{x,y,z\}$ and $\{\gamma,\phi,\psi\}$ of the rover frame with respect to the ground frame. The next two elements are the roll and pitch of the front platform with respect to the center platform. Closing out the state vector are the roll and pitch of the rear platform with respect to the center platform. Knowledge of this vector completely determines the position of the rover structure in inertial space.

The environment receives control commands for each time step evaluated. The commands are:

1) steering command (servo angle)
2) velocity command (drive motors signal)
3) range finder position command (servo angle)

The environment then integrates the rover heading and velocity to formulate the new position of the center platform. Next the position of the front and rear platforms are determined with respect to this new center platform location. This defines a new state vector for the following time step. Once the state vector has been determined the orientation of the sensors are calculated and a reading from each sensor is formulated. At the end of this time increment the simulation environment returns to the control code the following variables:

1) rover position
2) gyroscope/sun sensor reading (rover yaw)
3) inclinometer readings (rover roll and pitch)
4) front platform accelerometer readings (roll and pitch)

5) range finder and proximity sensor distance readings
6) contact sensor (bumpers) status readings
7) drag wheel distance reading

These variables are then used by the control code to produce commands for the next environment time step.

The only dynamics considered by the environment are those that occur on the time scale of the simulation time increment, usually around a tenth of a second. These variables have been found through experimentation to the be servo actuation of the steering and laser range finder [1]. Both of these systems are modeled as first order responses.

3.3 SIMULATION MODELING

3.3.1 Ground Profile Model

Ground Profile definition is accomplished through the elements of a ground profile matrix. Each element of the matrix represents the height of the ground at that location. By defining the ground profile in this way, there is no distinction drawn between the ground surface and obstacles. An obstacle is simply a higher area of the ground. The ground profile matrix divides the ground profile into discrete components. This division imposes a resolution onto the ground profile which can be varied to change the shape of obstacles and to operate the rover on different scales of travel.

Modeling the ground profile has been done in three steps. Initially the ground's large scale variations are produced. This can be done through multiple if-then statements or by a functional definition. On this scale, variation in the ground profile is on a larger scale than the dimensions of the rover. This models things such as hills and valleys.

In the second stage of ground profile definition, obstacles are placed on this underlying ground surface. These obstacles can take the form of sharp hills, cliffs, rocks and craters. Obstacles can be placed randomly on the ground surface or each obstacle location can be specified. To place obstacles randomly onto the ground surface, a desired percent of coverage and nominal obstacle size must be given. Obstacles are allowed to overlap each other, this produces a more realistic looking ground terrain. However, this overlap is only considered once in overall percent of coverage. The height of each obstacle can also be randomly varied or specified. This height can become negative to produce "craters" in the ground profile. For certain situations, a specified obstacle set up may be required. To create a specific obstacle distribution, the {x,y} location as well as the obstacle height must be given.

In the last stage of ground profile development, short bumps can be added to produce an overall surface roughness. Once these steps are complete their effects are added to the underlying ground matrix to produce the final ground profile matrix. This produces a very realistic and effective ground profile. An example ground profile can be seen in figure 3.2

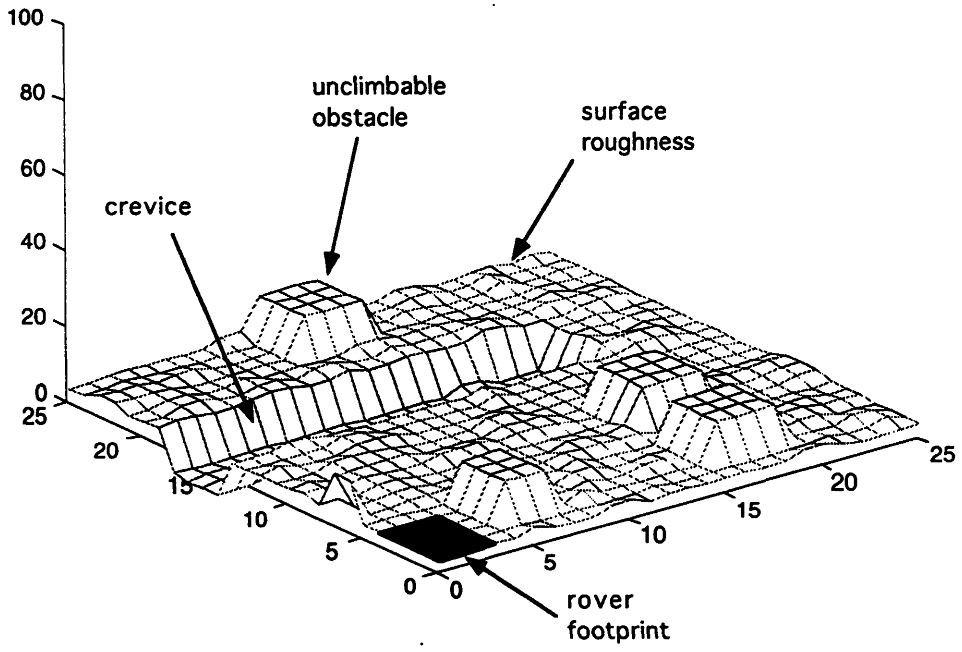


Figure 3.2: Example Ground Profile

Once this matrix has been developed the height of the ground profile is defined continuously over the entire range of the matrix. This is done by interpolating points between each element of the matrix. Planes are fit between the elements of the matrix along the forty-five degree line between the elements as seen in the figure 3.3.

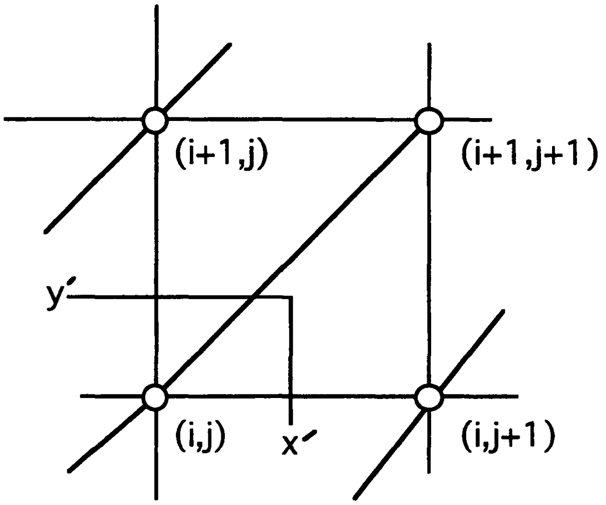


Figure 3.3: Ground Profile Matrix

Once these planes have been defined, the height of any point on the ground can be found by determining on which plane it lies. The relevant grid square for a desired location {x,y} is found by dividing by the grid resolution. Then {x',y'} is defined for the local grid square as seen in the picture. If x'>y' (as in the figure) with respect to the appropriate grid square, points (i,j), (i,j+1), and (i+1,j+1) are used to define the appropriate local ground plane. If y'>x' the point (i,j+1) is replaced by (i+1,j). These three points define a plane upon which the desired point lies. The corresponding ground height for this {x,y} pair can now be found.

This operation takes the form of a subroutine in the simulation environment. Given an {x,y} point in the ground reference frame a {z}, or height, value for the ground matrix is returned.

Determination of the ground profile in an actual mission would be done by stereo photography. A reconstruction routine has been developed to take such a stereo image and produce a ground matrix identical to the one used by the simulation environment [8]. Defining the ground profile in this way makes the simulation compatible with such photographic techniques. With this capability the control system can by tested on actual terrain data obtained by the rover. This is a powerful tool that allows the ground crew to simulate various runs over an actual ground surface prior to an attempt by the rover. This information can be used to aid the rover along its path.

3.3.2 Rover Platform Model

The rover platform is modeled kinematically. No mechanical dynamics are considered. Three rigid members are used to model the body of the rover. These members represent each platform of the rover. Four revolute joints are used to connect the members of the model. These four joints allow the front and rear platforms to rotate in pitch and roll with respect to the center platform. The joints are free to rotate, allowing unrestricted motion between platforms. Therefore, the position of the front and rear platforms are completely determined by the underlying ground profile. At the end of each individual member is a sphere. These spheres are used to represent the wheels of the vehicle. It was found that spherical wheels made the rovers reaction to changes in ground profile more realistic than disc wheels. The model of the rover can be seen in the figure 3.4.

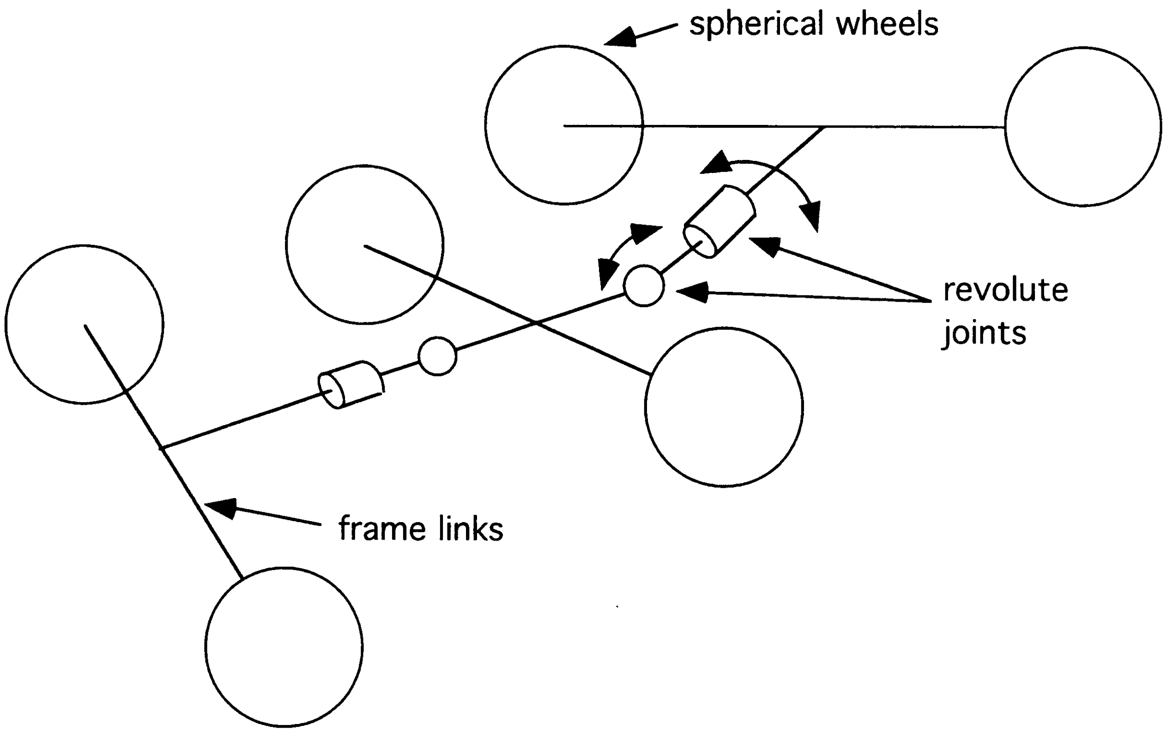


Figure 3.4: Rover Model

Center Platform

Since the rover coordinate frame is attached rigidly to the center platform, this platform is a the major determinate of the state of the vehicle. The {x,y} location of the center platform is calculated from the input commands of the control system. The {z} location of this platform is defined by the ground profile given its {x,y} location.

The roll of the center platform is defined by the left and right wheels, each wheel contacts the ground plane. This is accomplished using a numerical technique to solve the kinematics equations that determine the vehicle roll. The Newton-Raphson method is used to solve these equations. This method is also used in the determination of the pitch of the center platform and in the determination of the position of the front and rear platforms. A numerical method was required because of the non-linearity and complexity of the kinematic equations. The method of solution is discussed in the following section which describes its implementation with the front and rear platforms.

With the roll of the center platform determined the remaining variable is the platform pitch. Given only the ground profile and the spherical wheels the pitch of the center platform is unconstrained. To solve this problem two "artificial wheels" are placed in the model. These wheels are located to the front and to the rear of the center platform. These additional wheels are represented by spheres and constrain the pitch of the vehicle. Initially the pitch was defined by making the rover platform parallel to the ground profile. This constraint produced discontinuities in the motion of the center platform because of discontinuities in the slope of the ground profile. These additional wheels are used to smooth this motion and produce realistic values for vehicle pitch. The position of these wheels on the platform, as well as their size, were determined experimentally to emulate the actual vehicle motion.

Originally it was thought the height of the center platform would need to be modified when the rover climbed steep hills. In such a situation the center platform might loose contact with the ground surface. This height correction was calculated using the roll and pitch of the center platform. Correction factors for this purpose were determined experimentally with the actual rover platform. However this problem is now avoided using the rover model equipped with the "artificial" spherical wheels mentioned above.

Front and Rear Platforms

Accurate modeling of the front and rear platform position was the greatest challenge in the creation of an accurate rover model. Once the location of the center platform is calculated, the front and rear platforms are considered individually. Each platform is positioned such that both spherical wheels touch the ground profile at one point each.

Positioning the front and rear platforms is accomplished by solving two kinematic equations in two unknowns. The unknowns are the platform roll and platform pitch with respect to the center platform. The first step in setting up the kinematic equations is to define the ground plane beneath each wheel. This ground profile is represented by the equation of a plane under each wheel, and must be defined with respect to the rover coordinate frame. Once these ground plane equations are found the kinematics equations can be set up. The equations are given bellow (equation 3.2) for the location of the front right wheel in the rover frame as seen in figure 3.5

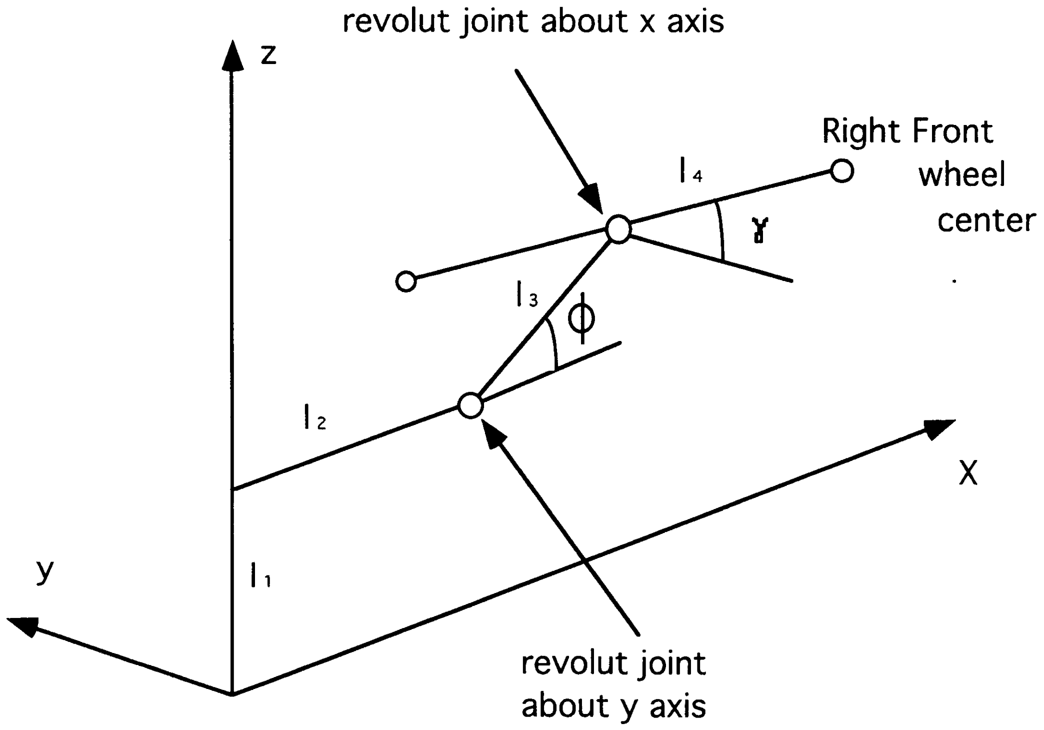


Figure 3.5: Front Platform Kinematic in Rover Frame

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{\substack{\text{right}\\\text{front}\\\text{wheel}}} = \begin{bmatrix} l_2 + l_3\cos\phi - l_4\sin\gamma\sin\phi \\ -l_4\cos\gamma \\ l_1 + l_3\sin\phi + l_4\sin\gamma\cos\phi \end{bmatrix} \qquad \text{(equation 3.2)}$$

where ϕ and γ represent the pitch and roll of the front platform with respect to the center platform, respectively. These equations represent the position of the center of each wheel in the rover coordinate frame. This point must be one wheel radius distance from the ground profile. To find the distance between the center of the wheel and the underlying ground profiles equation 3.3 is used:

$$R = \frac{|ax_0 + by_0 + cz_0 + d|}{\sqrt{a^2 + b^2 + c^2}} \qquad \text{(equation 3.3)}$$

Where a,b,c and d are the coefficients for the equation of the ground plane, R is the radius of the wheel and $\{x_o,y_o,z_o\}$ are the coordinates of the wheel center (as given in equation 3.2). Specifying the distance between the ground and the wheel center in effect produces a spherical wheel. This wheel radius defines a solution to the equation.

There exists more than one mathematical solution to these equations. For instance both wheels could be beneath the surface or one above and one below and so on. These problems are solved by initially guessing the position of the wheels above the ground profile. Therefore the numerical routine approaches a solution from above. This is, in effect, "dropping" the wheels onto the ground profile.

A very similar method is used for the rear platform as well as the pitch and roll of the center platform. The only changes would be in the geometric position and sizes of the linkage members.

3.3.3 Hazard Avoidance Sensors

Laser Range Finder

The primary source of information for the control systems path planner is the laser range finder. The range finder is modeled as a one dimensional beam of light. The range finder is physically located on the front platform and is situated on a rotating base. On the real rover this laser base is moved, in yaw, by a servo motor actuator. The response of the servo motor to a command signal is modeled as a first order response. This response is given by equation 3.4.

$$\psi'_{\text{actual}} = \frac{-\psi_{\text{actual}} + \psi_{\text{command}}}{\alpha} \qquad \text{(equation 3.4)}$$

Where ψ_{actual} is the actual servo angle, ψ_{command} is the commanded servo angle, and α is the range finder servo time constant.

Once the range finder angle has been determined, a new coordinate system is placed on the rover. This coordinate system models the position of the range finder. The origin of the coordinate frame is the pivot point of the range finder turn table. The $\{x\}$ axis of this new frame is pointed along the direction of the laser. The transformation between this range finder coordinate frame and the rover coordinate frame is described by the pitch and roll of the front platform and the yaw angle (servo angle) of the range finder.

Due to the piece wise definition of the ground profile an analytic solution to find the laser intersection with the ground profile proved cumbersome. So to produce a range finder distance reading, a vector is stepped out along the{x} axis of the range finder coordinate frame at a specified increment. This increment represents the resolution of the actual range finder. The range finder laser beam is then described by a constant multiplied by the {x} axis unit vector in the range finder frame. This beam is a vector that is transformed into the rover frame and then into the ground frame. Once the laser beam direction is known in the ground frame it is checked to see if it has intersected the ground profile. If there is no intersection the laser beam is steeped out one more increment until an intersection is found or the sensor's maximum range is reached. If there is an intersection the distance to this intersection represents the range finder reading. One range finder distance is returned to the control system for each time step.

Proximity Sensors

The proximity sensors on MITy-2 are close range optical sensors. These sensors are positioned on the front platform and are tilted downward ahead of the vehicle. Detecting obstacles, such as sharp drop offs, are the purpose of these sensors. A single sensor is located on either side of the front platform. These sensors can also be angled so that their beam passes in front of the front wheels. In this configuration they can also be used to detect unclimbable obstacles that are very close and the laser range finder has missed (similar in function to bumper sensors).

The proximity sensors are modeled in the same fashion as the laser range finder. A line representing the optical beam is found in the ground coordinate frame. Then successive steps are taken along this line until an intersection with the ground is found or the sensor maximum range is reached.

The sensors have a range of roughly twelve inches and resolution of a tenth of an inch. Both range and resolution are represented in the simulation.

Contact Sensors

bumpers

Contact sensors on the MITy rovers are in the form of bumpers. There is a bumper on the front and rear of the vehicle. These bumpers are the rovers last line of defense for obstacle avoidance.

Modeling of the bump sensors is similar to the other hazard avoidance sensors. A line is found that represents the physical orientation of the bumper. This line is first located in the rover frame and then transferred to the ground frame. Once a representation of the bumpers is possessed with respect to the ground frame, it is determined if this line intersects the ground profile. An intersection with the ground profile corresponds to a deflection of the bumper.

3.3.4 Navigation Sensors

Readings for navigation sensors are produced in the simulation as the motion of the vehicle is determined. For instance, the gyroscope and sun sensor readings are represented by the integrated value of the vehicle yaw (as discussed in the next section). The drag wheel reading is the integrated path length. Inclinometer readings correspond the pitch and roll of the center platform, and so on. Provisions exist to introduce such imperfections as noise, bias and drift into the navigation sensors.

3.3.5 Rover Motion

Rover motion over any given time step is considered two dimensionally and kinematically. Movement of the rover in the {z} axis as well as rotation in pitch and roll are not integrated to determine rover motion. Instead rover movement is considered in the {x,y} plane of the rover coordinate frame. Yaw of the rover and path length of travel are also integrated to complete the two dimensional approximation. This ignores the effects of the ground profile during integration. Instead the rover is adjusted to the new ground location after the given time step. Since the rover motion per time step is very small with respect to variations in the ground profile, this method gives a good approximation of rover motion. Motion is accomplished through the integration of rover velocity for the given time step. The change in position is integrated from a velocity and steering command given to the environment by the control system. The method of numerical integration is a fourth order Runga-Kuatta technique. This technique uses a variable time step that checks tolerance of all the variable to .01% [1].

In the integration of rover motion the rover is considered a symmetric vehicle with the front and rear wheels turning in opposite directions. The width of the vehicle is reduced to zero. This model was adapted from the existing two dimensional simulation and has been verified with the actual rover through testing [1]. Since the steering mechanisms are located on the front and rear platforms the roll of these platforms will affect the total amount of rover turn. Since the front and rear platforms were modeled symmetrically the average of the two platform's roll is used. The rover model used in rover motion is shown in figure 3.6

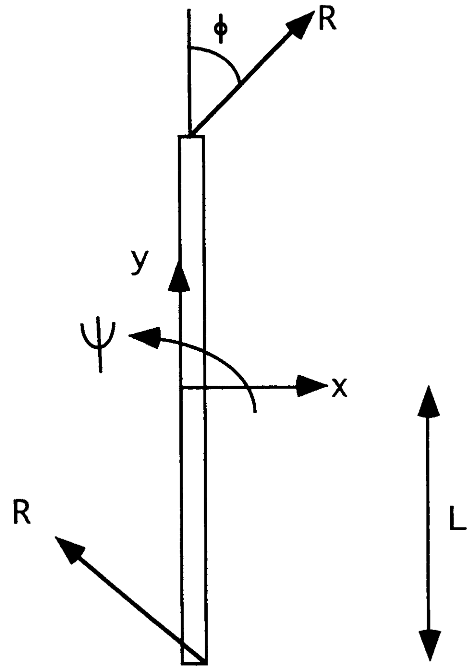


Figure 3.6: Rover Motion Model

where R represents the rover wheel velocity vector, L the effective turning radius, ϕ the rover steering angle, and $\{x,y,\Psi\}$ the rover reference frame. The rover motion is integrated along with the servo responses from the following equations.

$$\psi' = \frac{R\sin\Phi_{\text{actual}}}{2L}(\cos\gamma_{\text{front}} + \cos\gamma_{\text{rear}}) \qquad \text{(equation 3.5)}$$

Equation 3.5 is the equation of motion for vehicle yaw. ψ represents the yaw of the rover in the local frame, R the rover velocity and Φ_{actual} the actual steering angle. The cosine of the roll (γ) of the front and rear platforms are also considered. This will effect vehicle steering.

$$\begin{aligned} \dot{x} &= R\cos\Phi\cos\left(\frac{\gamma_{\text{front}} + \gamma_{\text{rear}}}{2}\right)\cos\psi \\ \dot{y} &= R\cos\Phi\cos\left(\frac{\gamma_{\text{front}} + \gamma_{\text{rear}}}{2}\right)\sin\psi \end{aligned} \qquad \text{(equation 3.6)}$$

The and x and y equations of motion differ only by the sine or cosine of the vehicle yaw. This motion is also effected by the roll of the front and rear platforms due to the change in steering attitude.

$$\dot{s} = R\cos\Phi\cos\left(\frac{\gamma_{\text{front}} + \gamma_{\text{rear}}}{2}\right) \qquad \text{(equation 3.7)}$$

In equation 3.7, s represents the path length of the rover motion.

$$\Phi' = \frac{-\Phi + \Phi_{\text{command}}}{\alpha_{\text{steering}}} \qquad \text{(equation 3.8)}$$

The steering servo response is given by equation 3.8, where Φ is the actual steering angle, Φ_{command} is the steering servo command, and α_{steering} is the servo time constant. This is a first order response representation of steering servo location.

Once the rover motion has been determined in two dimensions this motion is changed to three dimensions through a coordinate transformation. Once the new $\{x,y,\psi\}$ location is found in the global frame the rover is adapted to the ground profile. First , the height of the rover frame is adjusted so that this frame rests on the ground profile. Then the roll and pitch of the center platform is determined. Finally the locations of the front and rear platforms are calculated. This completely updates the position of the rover structure.

Problems with this method would occur if the environment time step was large. The smaller the time step the more often the three dimensional effects are considered and the better the approximation to true rover motion. In the current simulation the cycle rate is around 10 Hz. This corresponds to much less than one inch of rover travel and is quite adequate.

3.4 SIMULATION PERFORMANCE AND EVALUATION

Performance

The full simulation, three dimensional environment integrated with rover control software, has been in operation for quite some time. The rover has been simulated on many different types of terrain in many different runs. The rover simulation has proven quite accurate and reliable. The simulation can be trusted in climbing obstacles up to approximately ten inches in height. Above this height problems may crop up with the solution of the front and rear platform positions. However, this is a higher obstacle than the actual rover will ever be expected to climb, so it is not a major problem. The rover simulation has performed well under all required conditions.

Rover/Simulation Correlation

In order to correlate the simulated rover motion with actual rover motion, data was taken as the rover climbed steps of varying height. This test provided information on the rotation of the rover platforms and was used to verify the kinematic model. Figure

3.7 shows the maximum angle of the front platform as the rover climbed steps of varying height. In this situation the rover's front wheels rest on the top of the step.

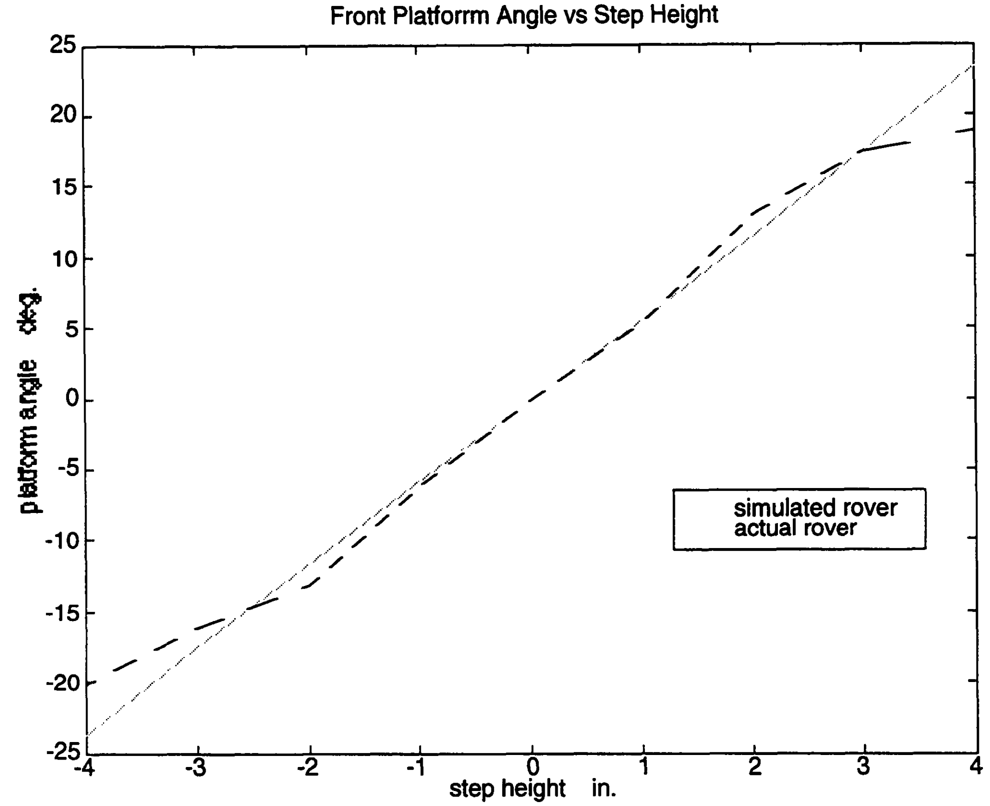


Figure 3.7: Front Platform Angle vs. Step Height

This shows excellent correlation from small steps with some deviation at larger step sizes. This is due to the mechanical interaction between the front and center platforms on the actual rover. On the actual rover, raising the front platform affects the angle of the center platform because of the spring steel connections. This coupling becomes significant at larger step sizes. The center platform will deflect 6° when the front platform is on a 4" step. These two platforms are decoupled in the simulation.

Some of the rover/simulation correlation can be done qualitatively. The animation software described in the next section shows the rover as it climbs different obstacles. This allows for a visual verification of rover motion. This visual "ball park" check on rover motion was invaluable in creating a realistic rover model.

Animation

The rover simulation has been integrated with animation software developed with the use of a Silicon Graphics computer [16]. This animation software allows the user to view the rover as it travels across the ground profile.

The simulation's main window depicts the rover and the underlying ground profile. Specifications were made for the animation software to ensure it would complement the simulation. All sensors are seen on the rover platform along with lines that represent the laser range finder and proximity sensors readings. Along with this main window is a control window. In this control window animation parameters can be changed and simulation variables can be viewed. The vantage point from which the rover is viewed can also be varied. This was required to provide the user with the best visual information on rover motion.

A picture of the simulation animation is shown in figure 3.8.

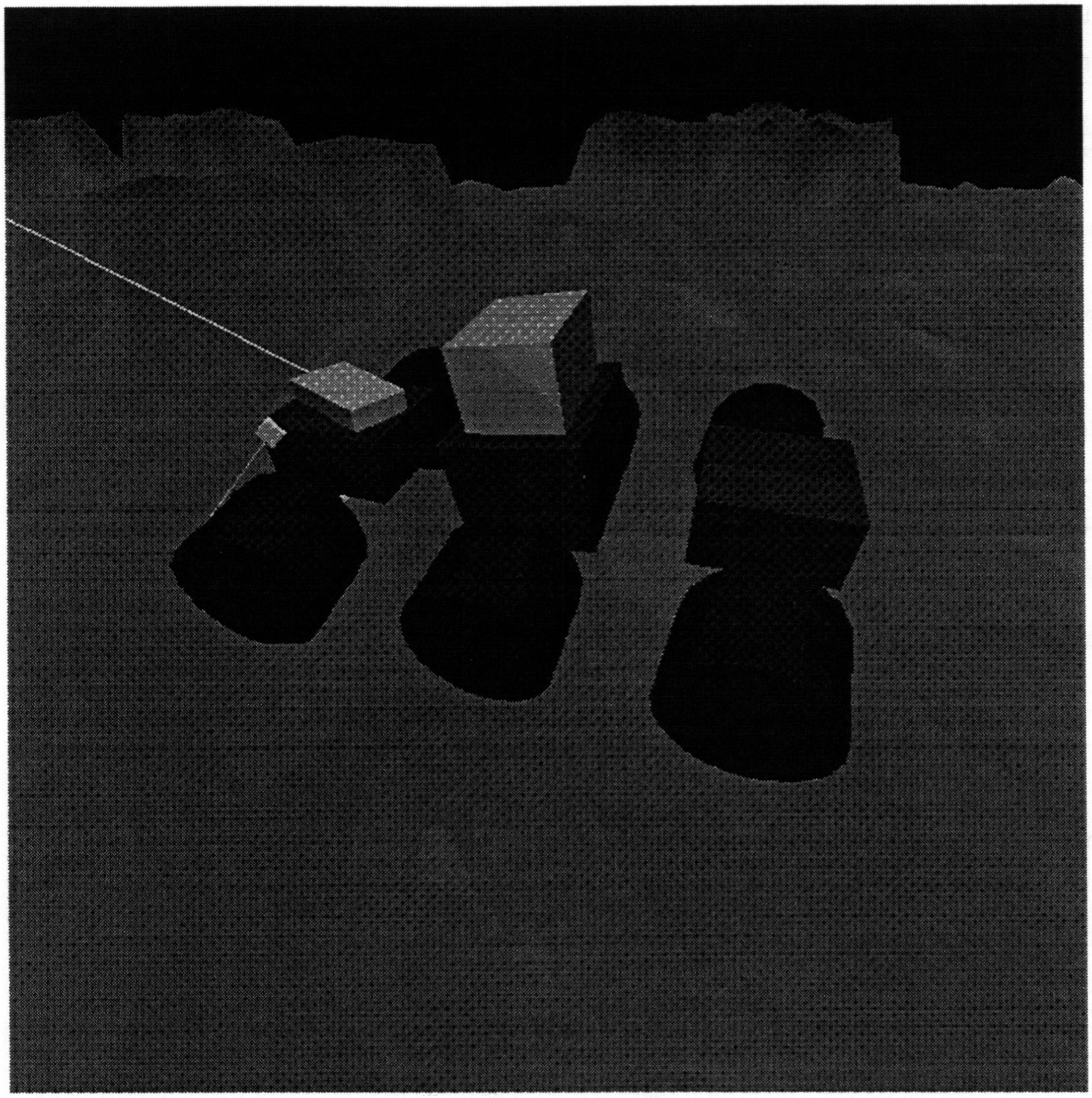


Figure 3.8: Three Dimensional Simulation Animation

Initially the rover simulation was run to completion and data from this run was stored in data files. These results could then be viewed with the animation software. The simulation and animation software have been integrated recently so the rover can be viewed as the simulation is executing.

This animation was very useful in debugging the simulation. Without the animation it was practically impossible to find out what the rover was doing and what kind of surface it was encountering.

The animation allows for a very qualitative evaluation of rover performance in all simulated three dimensional scenarios. This intuitive feel is also invaluable when trying to determine how to improve the rover system.

3.5 RESULTS AND RECOMMENDATIONS FOR HAZARD AVOIDANCE

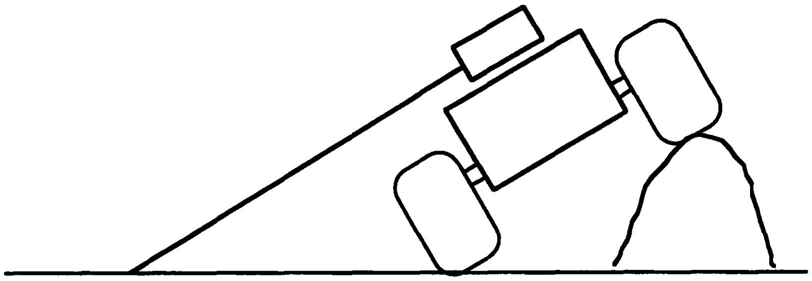
3.5.1 Problem Situations and Control System Improvements

Results from Actual Rover Testing

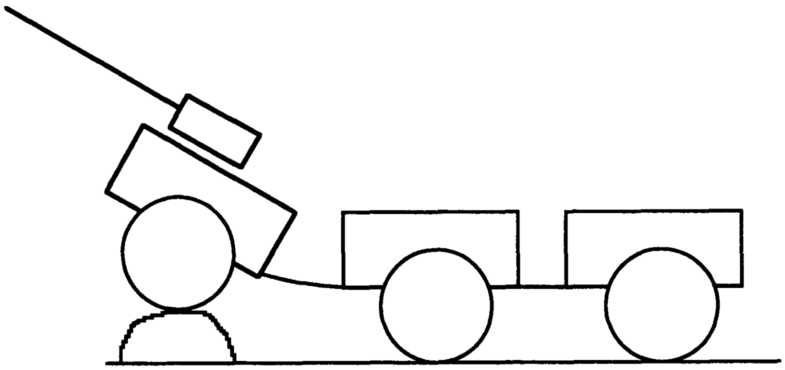
During actual rover testing problems were discovered as the rover traveled over rough terrain. As the rover platforms tilted the attitude of the various hazard avoidance and navigation sensors were changed. This often meant that the sensors were not operating as intended and vehicle performance was greatly reduced. These problems were recreated in simulation so that solutions could be found.

Laser Misdirection

The most obvious and detrimental problem was the misdirection of the laser range finder. As the range finder moves in yaw and the front platform rolls and pitches, the laser is often pointing out of the plane of the local ground profile. This means the laser could be looking straight into the air or straight into the ground. Tilting of the laser causes the rover to think that there is an obstacle present (or there is not on obstacle present) that really does not exist (or does exist). This problem is illustrated in figure 3.9.



a) laser points at the ground



b) laser points into the air

Figure 3.9: Laser Misdirection

Obviously this can cause the rover to avoid an area unnecessarily. This problem was seen in actual rover testing and was easily recreated in simulation.

To resolve this problem the laser readings were incorporated with information about the roll and pitch of the front platform. This allows the height of the obstacle seen by the laser to be determined The laser reading is then considered reliable if the height of the obstacle is higher than the maximum climbing height. This eliminates the ground as a source of unrealistic obstacles.

Rock Climbing

Other problems are encountered as the rover climbs rocks. This situation effects the laser range finder as well as the proximity sensors. As the front platform rose to overcome the obstacle, the proximity sensors would be lifted up and erroneous distance reading would be encountered. Figure 3.10 illustrates this situation. This would appear to the rover as a cliff of sharp drop off, and would cause it to stop.

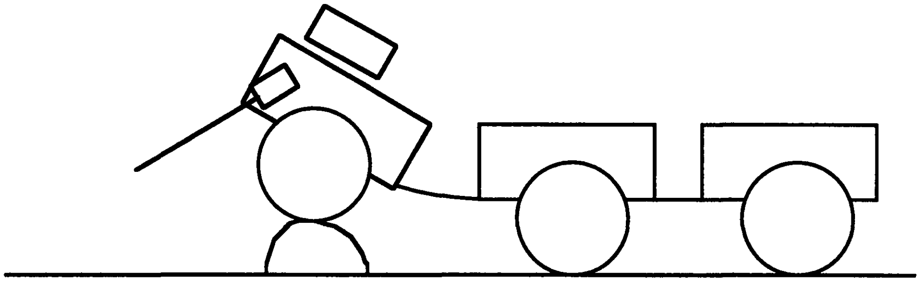


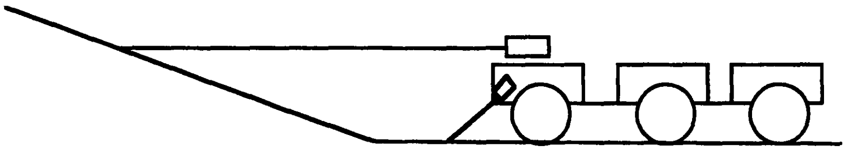
Figure 3.10: Proximity Sensor Misdirection

To solve this problem it was decided not to use the proximity sensors when the pitch of the front platform was large. Selective use of these sensors only allow the sensors to be utilized when the sensor is operating as intended.

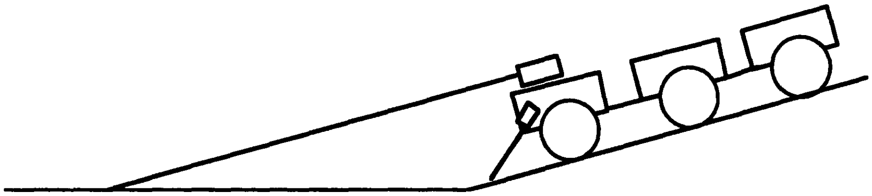
Valleys and Hills

The surface of the moon has hills and valleys with a wavelength on the scale of the rover length [10]. For this reason the simulation was run over this type of terrain.

These valleys and hills presented challenges to the rover hazard avoidance system. As the rover approaches a hill (Figure 3.11a) or comes down into a valley (Figure 3.11b) the range finder sees the hill or valley as an obstacle.



a) approaching hill



b) approching valley bottom

Figure 3.11: Hills and Valleys

This situation will cause the rover to avoid this region unnecessarily. This unnecessarily motion did not generally cause a rover mission failure but did increase the path length traveled by the rover. With the information the rover has, these situations are difficult to identify.

When the rover approaches a gradual hill (figure 3.11a) it will turn to one side to avoid the perceived obstacle. As it comes closer to the hill the rover will begin to climb the hill and orient itself with the hill slope. Then the rover will travel again as if it is on level ground.

A valley presents a similar challenge. As the rover travels down the side of the valley, the laser will identify the bottom of the valley as an obstacle. To avoid this "obstacle" the rover will begin to turn. Then as the rover approaches the bottom of the valley, the rover platform will slowly begin to orient itself with the bottom of the valley. The rover will again travel normally as it is on level ground. This only increases the distance traveled by the rover and generally does not produce a failure to reach the target.

The distance the rover is looking or planning ahead is very important in these situations. The simulation was used to tune this maximum planning distance. This planning distance varies with the type of terrain the rover is likely to encounter. The further the rover looks ahead, the more these situations will effect it. The less the rover looks ahead, the less it will plan ahead. This design trade off was balanced in the simulation for different types of terrain.

Cliffs

Cliffs or sharp drop-offs are an obvious problem for the rover. A steep crevasses could bring an early end to a rover mission. This problem was foreseen in the design of MITy-2. For this situation the rover uses proximity sensors to identify and avoid drop-offs. These sensors are sampled at a rate of ≈1 Hz. This sample rate was constrained by the power consumption of the sensors. With this sample rate and the rover speed it is possible that the rover will identify a cliff too late and not be able to recover. Obviously this could present major problems.

To determine the necessary rate at which the proximity sensors were sampled a cliff situation was created in the simulation. This sample rate was tuned so the rover put its front wheels right to the edge of the cliff before halting. This situation was deemed adequate for current rover applications. Rover speed would most likely be decreased and/or sensor sample rate increased in a real mission.

3.6 EXPANSION OF ROVER SIMULATION AND FUTURE WORK

The three-dimensional simulation has performed well in the evaluation and improvement of the rover's hazard avoidance software. But this is not its only use. New applications of the simulation are currently being implemented and others are planned.

3.6.1 Deployment Mechanism Testing

One additional application of the simulation is its use in testing the deployment mechanism discussed in chapter five of this thesis. Integration of this mechanism with the simulation is now in progress and animation is being developed to display this additional hardware.

Initially the existing deployment mechanism will be modeled to verify the design. If changes need to be made to this design these changes can be first evaluated in simulation.

System Modeling

The deployment mechanism is a two degree of freedom device. Each motor is being modeled in simulation with a first order response. The time constant of the motors was determined by experimentation with the actual mechanism. The mechanism is being placed on the rear platform of the rover and animation software to view this in simulation is being produced. Also, control algorithms are being developed to command the rover during this operation.

Sensors for Positioning

As discussed in chapter five positioning of this mechanism is a challenging problem. Various techniques are discussed to achieve this positioning. Some of these techniques utilize various kinds of sensors; contact, optical, etc. It is planned to use the simulation to evaluate these different types of sensors and their application to mechanism positioning.

3.6.2 Integration with Ground Station

Work is also in progress on the integration of the simulation with the current rover ground station software. This software exists on a personal computer and is used to teleoperate the actual rover. In order to incorporate the ground station, rover simulation and animation, the ground station is being transferred to UNIX/Xwindows format.

This will allow the rover to be operated in simulation, through the ground station, just as the real rover is currently operated. With this capability the user can simulate the motion of the rover through a field before it is attempted by the actual rover. It will also allow various modes of rover teleoperation can be tested through simulation.

3.6.3 Testing of new Hazard Avoidance Packages

As an extension of the planetary rover work being conducted at Draper Laboratories, a new project has begun. This project is developing an autonomous rover for earth based applications that is larger and better equipped than the MITy rovers.

For this new project, more sophisticated vehicle control software is being developed. To speed the development of this software, the existing rover simulation was utilized. Currently the rover simulation is being used to verify this new hazard avoidance package.

DEVELOPMENT OF THE MITY-3 MICRO-ROVER
CHAPTER 4

4.1 MITY-3

4.1.1 Design goal

MITy-3 was conceived as a mechanical upgrade of MITy-2. The hope of this new rover was to create a more mobile vehicle. It was hoped that this could be done and still maintain the strengths of the MITy rover platform, such as simplicity and reliability. Also, It was initially thought that there would be no major electrical changes from MITy-2 to MITy-3, this was intended to speed the construction of the third prototype rover.

A major change from the second to the third prototype rover was the use of conical wheels. This was to increase mobility by reducing the likely hood that the rover will become "high-centered", as seen in previous rover designs. With the use of these new wheels came a host of new challenges, including new structure, new motor driver circuitry, and a new steering system.

4.1.2 Processing

The ZILOG Z-180 micro-processor was chosen for use on the third prototype. This is the same processor utilized on MITy-2. Having been fully implemented on the second rover, this processor had proven itself in this application. The main advantage in using this processor was its familiarity to the group. Also, this allowed for portability of software from one rover to the other. The same software architecture developed for MITy-2 is now used on MITy-3.

4.1.3 Sensors

To speed in the construction of the third rover, it was decided to use the same hazard avoidance/navigation package developed for MITy-2. Each sensor has been built, implemented, and tested on the second rover, and has proven adequate.

Currently, due to time constraints, no hazard avoidance sensors have been implemented on MITy-3.

4.2 LIMITATIONS OF THE MITY-2 DESIGN

4.2.1 Mobility

The MITy-2 rover has good climbing ability and is a highly mobile robot. However there are some situations that show the vulnerability of MITy-2's design. In general, the worst mobility scenario for a rover is for it to become stuck and not be able to recover. This would defeat the entire idea of the autonomous mobile robot, and constitute an early end to the mission. For these reasons this scenario must be avoided whenever possible.

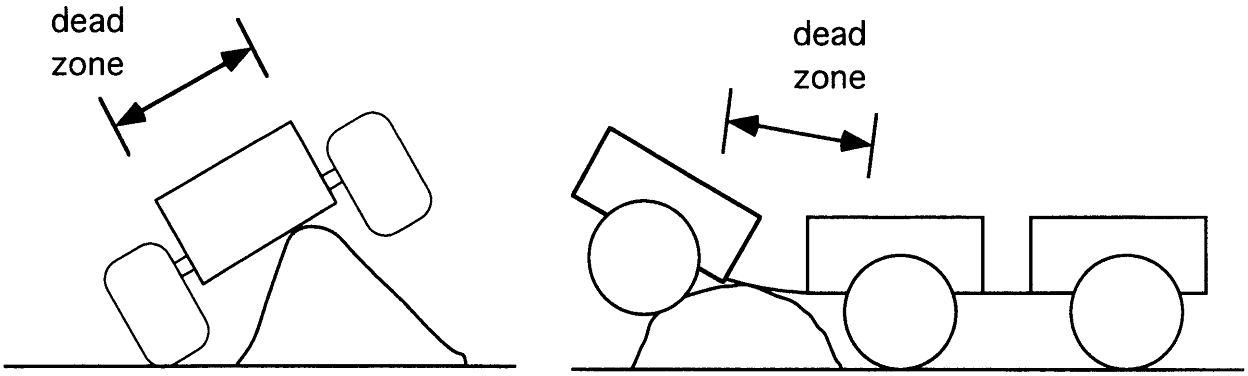
Testing

As one measure of mobility MITy-2 was tested using a step obstacle. The rover was driven over steps of varying height to help quantify its climbing ability. MITy-2 is capable of climbing an step that is 11.4 inches (29 cm) high. This corresponds to 190% of its own wheel height.

MITy-2 was also subjected to mobility testing in harsher environments, including a sandy beach and a rock bed. No great mobility problems were encountered on the sandy surface, however, some problems were experienced with the navigation and hazard avoidance sensors. Generally navigation tracking was slightly compromised due to the soft surface. Also, the laser range finder was affected, the sandy surface produced unreliable range readings.

A significant mobility problem was encountered in the rock bed. Although, the rover was capable of climbing many rocks of varying size it often became stuck when a rock hit the exposed underside of the vehicle. This space, between the wheels, is an area of great vulnerability when climbing larger rocks. As seen in figure 4.1a), a rock will strike the underside of the rover, the weight of the rover is taken off the wheels, causing a reduction in wheel traction. In this situation there is a large frictional force required to drag the rover across this rock. The combination of these two circumstances makes it very difficult for the rover to move. This often leads to the rover becoming caught.

Another area of vulnerability is the space between the rover platforms. This area, where the platforms are connected by the spring steel rods, is another unpowered region where the rover can become "high-centered". This problem was seen less often because the geometry requires a more specific size of rock. To high center the rover the rock must fit between the axles and still be tall enough to touch the vehicle's underside.



a) dead zone between wheels b) dead zone between platforms

Figure 4.1: Rover High Centering Problem

This is a very qualitative analysis of the testing performed on MITy-2, but these problems presented themselves clearly. If a more mobile rover is to be designed a solution to these problems must be found.

4.2.2 Steering

MITy-2 uses an Ackerman steering system, similar to that used on conventional automobiles. This system utilized a servo motor on each steering axle to provide actuation. The current MITy-2 steering servo motor outputs, after gearing, 112 oz.-in. of torque. This has proven to be marginally adequate, allowing steering only when the rover is in motion.

Some problems have been encountered with this steering system. For instance, as the rover is moving forward, if one rover wheel hits an obstacle the force provided by the rest of the rover to surmount the obstacle is reflected back to the steering servo. This requires a large servo torque to hold the steering system in place in the face of this large disturbance. This situation is illustrated in figure 4.2. In the current system this results in a large electrical power drain in the servo. Also this large torque has proven to be too much for the current servo gear train, as it has "stripped" many sets of gears.

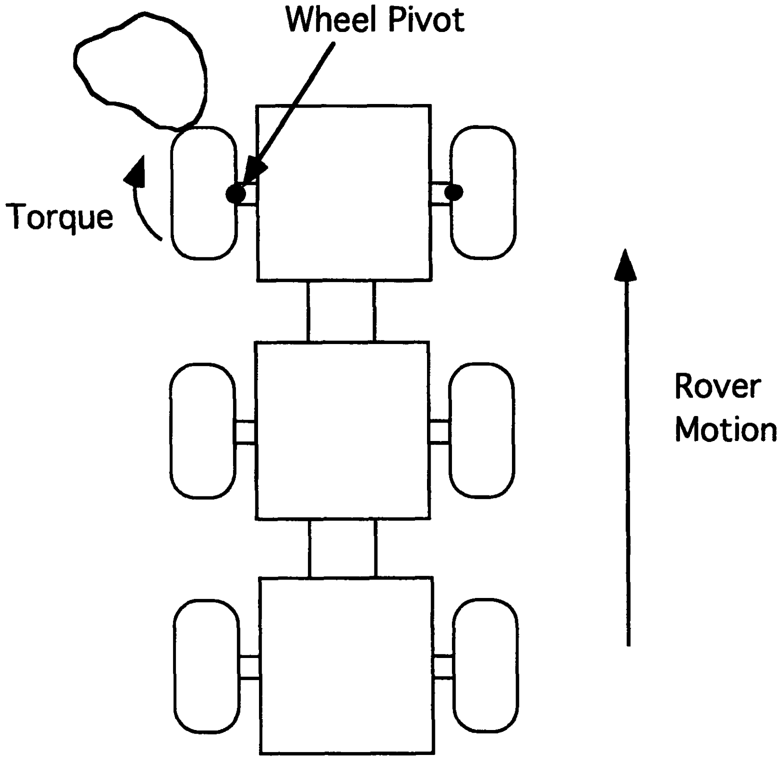


Figure 4.2: Wheel Disturbance torque

Also, in the current design, very large motor torque is required to turn the wheels when the rover is traveling at slow speeds. This is due to the large friction force, between the wheel and the ground, that needs to be overcome to pivot the wheels when the wheels are not rolling. This can be a problem when maneuvering in tight spots, as the rover is often required to do.

In short, the actuation force needed for conventional linkage steering becomes very large when maneuvering over rough terrain. This problem is worsened when high-mobility, or "fat", tires are used.

4.3 MITY-3 MOBILITY AND STEERING ISSUES

4.3.1 Mobility

As discussed earlier, a major problem seen with MITy-2 was its tendency to get caught on rocks in the "dead zone" underneath the vehicles. To alleviate this problem it was decided to use conical shaped wheels on MITy-3. These wheels extend over much of the width of the rover, practically eliminating the dead zone between the wheels. The use of conical wheels may not increase the nominal size of an obstacle that can be surmounted, but it was believed they would greatly reduce the risk of the rover becoming stuck or hung up on an obstacle. With this decision came the need for a new steering mechanism to actuate these conical wheels.

Conical Wheels

With the use of conical wheels it was hoped to increase the overall vehicle mobility by reducing the dead zone area on the underside of the vehicle. When the vehicle is viewed from the front, as in figure 4.3, it is clear how these new wheels will aid in the mobility of the rover. A problem that is not solved by conical wheels relates to the dead zone found between vehicle axles. This area is still vulnerable to obstructions.

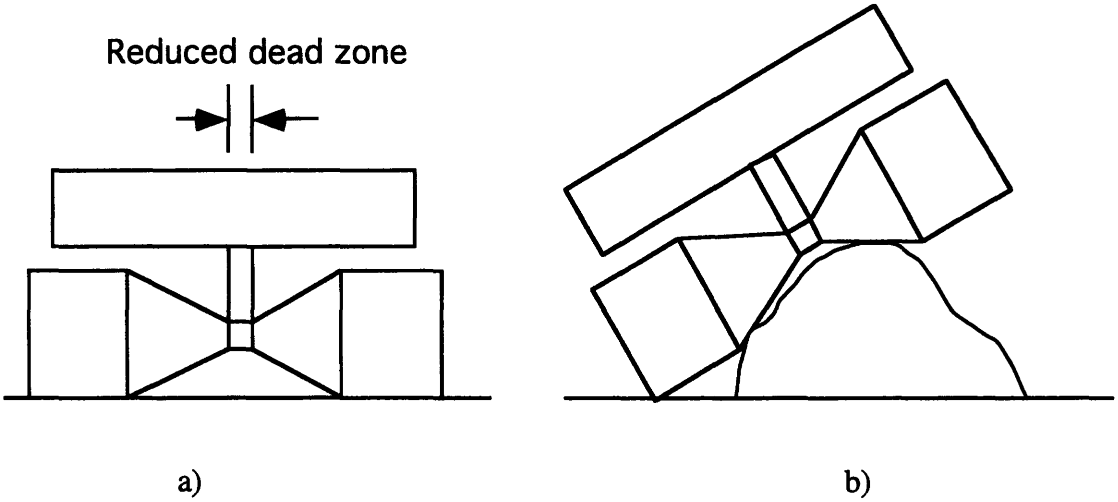
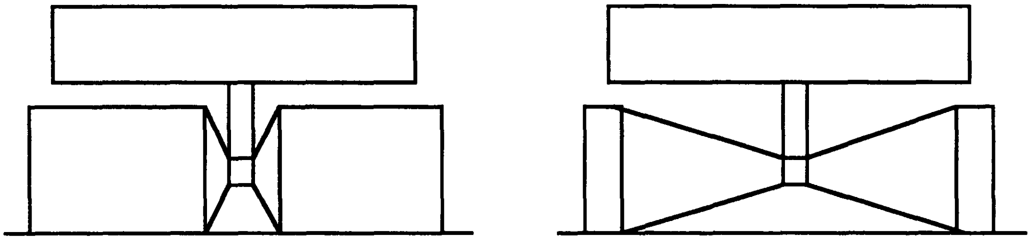


Figure 4.3: Conical Wheels Reduce Dead Zone

Over flat terrain, figure 4.3 a), the cylindrical portion of the wheel is all that is in contact with the surface. Here the conical wheel acts identically to a standard wheel, and the cone section does nothing. When the rover encounters rough terrain the cone portion of the wheel will often come into contact with the ground surface, figure 4.3 b). Since the cone portion is also powered, it can aid climbing.

A decision had to be made on the exact shape of the conical wheels. Taken to one extreme, the cone could become a cylinder that extend over half the width of the rover, as in figure 4.4 a). In this scenario, any small rock would disturb the attitude of the vehicle, this is undesirable because often rover attitude affects sensor performance. At the other extreme the cone could become the entire wheel, with only a thin disc at each end, as in figure 4.4 b). With this arrangement, vehicle traction on flat ground is sacrificed due to reduced wheel contact. It was decided to strike a balance between these situations by keeping the wheel cylinder approximately the same size as used on MITy-2.



a) large cylinder conical wheels b) large cone conical wheels

Figure 4.4: Different Conical Wheel Types

Conical wheels have been implemented on other vehicles, a conical wheel system is used on a rover being developed by the Russian space agency. This has given the Russian vehicle a very high degree of mobility.

The use of conical wheels causes major changes in many other areas of the rover design. The implementation of such a system has to be justified by a large increase in vehicle mobility and/or reliability. A major goal of the MITy-3 rover was to assess this decision and determine if the change is justified.

4.3.2 Steering

Steering on MITy-3 has undergone a major change. The use of conical wheels greatly reduces the risk of "high-centering" the vehicle on an otherwise surmountable obstacle. With this advantage in mobility, comes great difficulty in steering. Conical wheels make the use of steering linkages very difficult. Since each wheel essentially stretches half the width of the vehicle, there is no place to attach the wheel to the rover structure other than at the center point. Given this fact, to steer the vehicle the entire wheel axle must be pivoted about this center point in order to orient the wheels. A very large torque is required about this center point to turn the vehicle axis, as illustrated in figure 4.5. The amount of torque required to pivot the wheels on MITy-3 is about ten times the amount required on MITy-2.

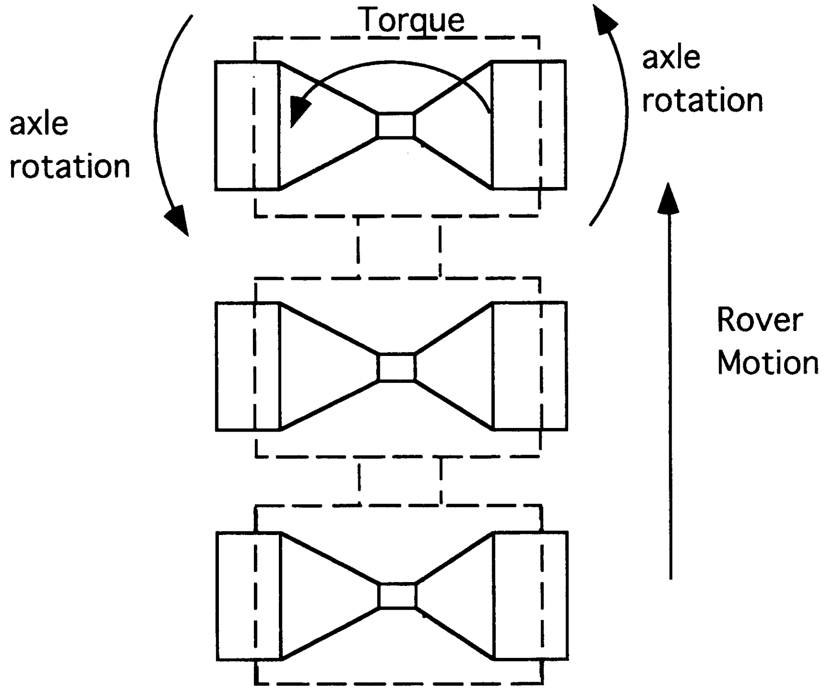


Figure 4.5: Steering Torque

Actuated Steering

One solution to this steering problem is to place a motor along the steering pivot axis. This motor would provide the torque required to pivot the wheel axle, as in figure 4.6. Also, when an obstacle is encountered on the end of the wheel, as in figure 4.2, this steering actuator would need to provide the torque to hold the wheel axle in place as the vehicle climbs the obstacle.

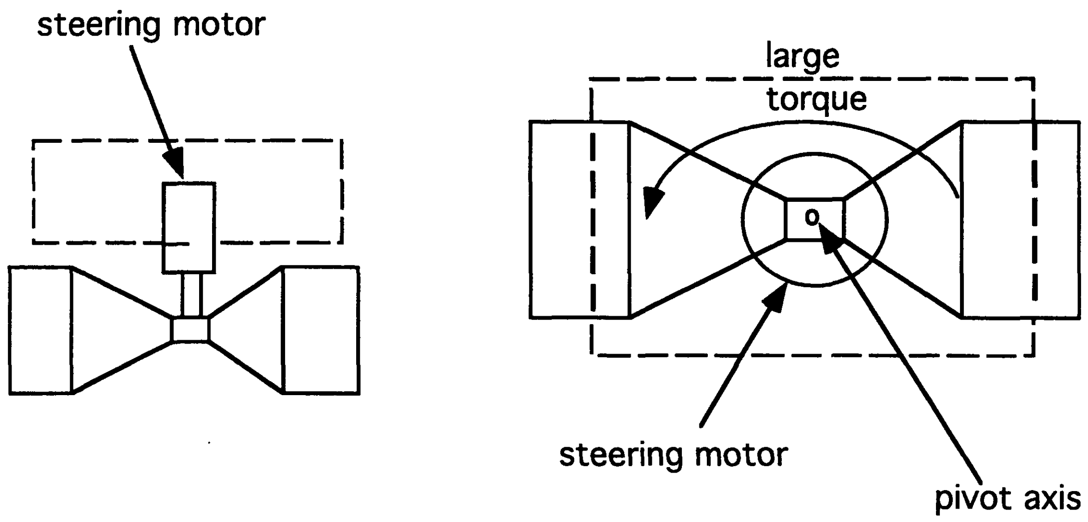


Figure 4.6: Actuated Steering

limitations on linkage

On previous rovers this steering motor was assisted by a steering linkage system which allowed the wheels to pivot about a point close to the wheel. To turn the wheels in this configuration, much less torque is required from the steering actuator (figure 2.2), although this torque is still large for "fat" tires. Since the conical wheels rotate over their entire length, there is no place to attach a linkage other than the center of the axle. The torque required to steer the wheel axle must be applied at this steering pivot axes. Since the distance between the pivot axes and the contact point between the ground and wheel is large, a very large torque is required.

actuator size and power

This large torque requirement makes it very unattractive to use a simple servo motor to actuate the steering. Such a motor would have to be larger torque than the actual wheel drive motors. And due to size, weight, and power constraints this is not practical.

Also, to hold the axle at any given steering angle the steering motor must be producing torque at all times. Providing torque means drawing current, and this requires electrical power. Due to the large torque required this will be a significant amount of power.

Tank Steering

Tank steering is a system which uses different wheel speeds to turn the vehicle. As the name implies it is the steering system utilized by military tanks as well as some heavy equipment such as bulldozers and back hoes. In a tank steering system the wheel axles are locked in place. Turning the vehicle is accomplished by moving the wheels on one side of the vehicle at a different speed relative to the wheels on the opposite side of the vehicle. For example, to turn left, the wheels on the right side of the vehicle are driven at a higher speed than the wheels on the left side of the vehicle. This produces a vehicle rotation to the left, as seen in figure 4.7.

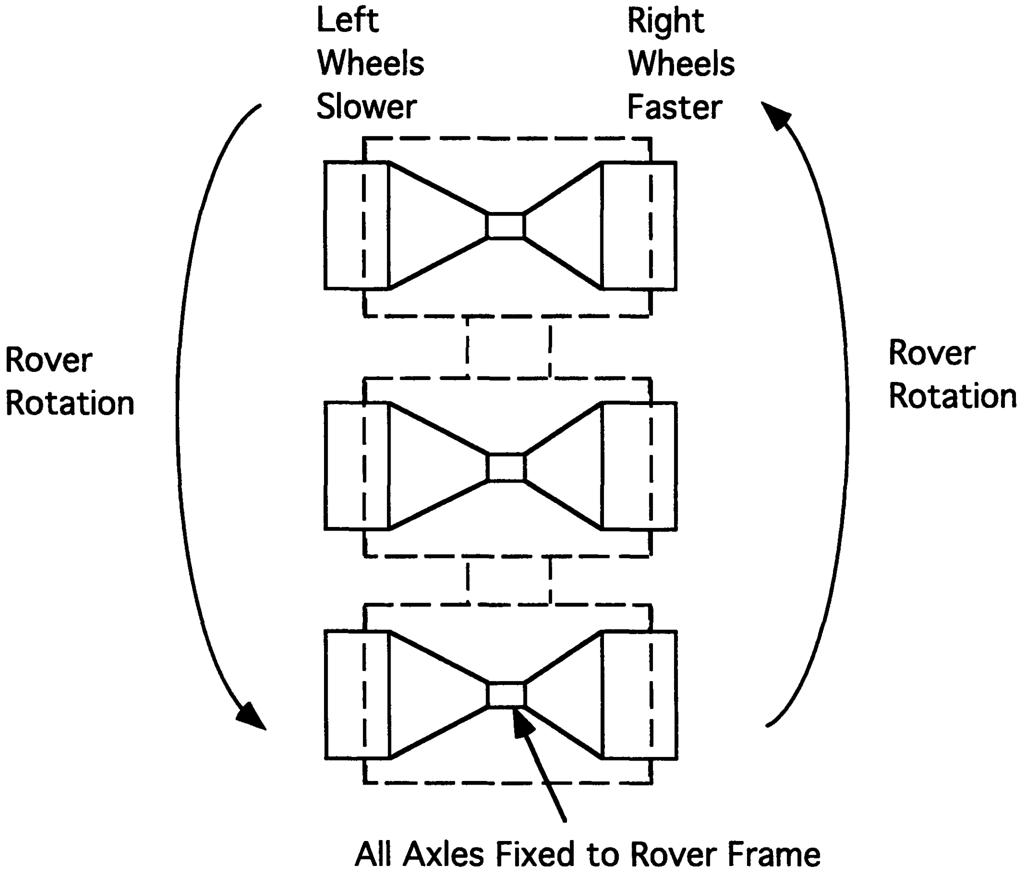


Figure 4.7: Tank Steering

Tank steering requires no additional motors to actuate the steering system. Steering is accomplished by the high torque drive motors that are already in place.

reliability

Tank steering is a very simple system since the only moving parts are the wheels themselves. Obviously this introduces a high amount of reliability since there are less moving parts to fail. This system inherently introduces redundancy in the steering actuation since there are three drive wheels on each side of the vehicle.

Another advantage of tank steering is the lack of a built in turning radius. Since the motors can be driven in either direction, the rover is capable of turning with a zero turning radius. This is accomplished by driving the wheels on one side of the vehicle in one direction, and the other side at equal speed but in the opposite direction. This can be extremely useful while maneuvering in tight situations.

efficiency

However, with the benefits of simplicity in this system comes a high degree of inefficiency. Since, as the vehicle turns, each wheel travels around a different arc, wheel slip is inherent. Also, the motion of each wheel will not be along it's direction of roll. This is especially true in sharp turns. Tank steering requires a large amount of wheel slippage and wheel dragging, and introduces great inefficiency. This problem is increased on a vehicle with a high length to width ratio, such as the MITy rovers.

The use of conical wheels to aid in vehicle mobility is also employed by the Russian Mars rover. To steer their rover the Russian space agency employs tank steering. However, the Russian rover is powered by a small radioactive thermal generator (RTG). This unit provides the rover with plenty of electrical power, so the inefficiencies of tank steering are not as significant. Due to cost and safety concerns the use of this power system was not considered for the MITy series.

mobility

The fact that the wheel axles are locked during tank steering can aid in vehicle mobility. This ensures that the wheels are always held firmly in position and firmly against the obstacle they are climbing. With the wheels firmly in position, all wheels aid in climbing. This is not the case with all steering systems.

Free Pivot Steering

The concept of free pivot steering for steering has many advantages. In free pivot steering the wheel axle is allowed to rotate freely about its center. This allows the wheel axle to be rotated to any given steering angle. With the axle pointed in the direction of the turn the wheels are always rolling in the direction of the turn. In the current system on MITy-3 the axle can rotate 90° in either direction. This motion is limited by the wires that provide electrical power to the motors.

In this steering system the axle is rotated to this position using the same motors that are used to propel the rover. To rotate the axle the wheel motor on one side of the axle will be driven at a different speed with respect to the wheel motor on the opposite side of the axle. For example, to pivot the axle to the left, the motor on the right side will be driven faster than the motor on the left side, this is shown in figure 4.8. Once the axle is pivoted, the rover will turn along a path corresponding to the axle rotation. This use of differential speed to rotate the wheel axle removes the requirement for an additional steering actuator.

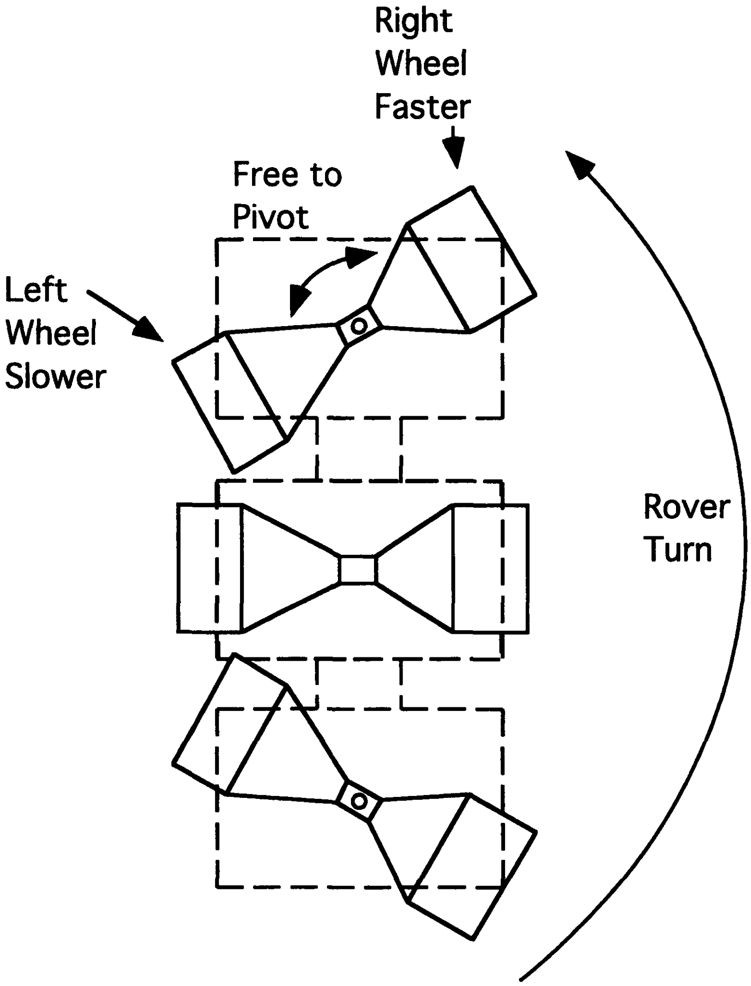


Figure 4.8: Free Pivot Steering

Like tank steering, the concept of free pivot steering uses the existing, high torque drive motors to actuate the steering system. Unlike tank steering, the drive wheels are oriented to roll in the direction of rover motion. With free pivot steering there is also no set limit on the turning radius of the rover. Since the wheel axles can be pivoted 90°, the rover can make a turn with a zero turning radius. Also, to accomplish a zero-radius turn, no wheel slip is required (assuming thin wheels), since each wheel rolls, not slides, in the direction of rover travel.

reliability

Free pivot steering has a certain degree of reliability inherent in the idea. Each axle contains two wheels, therefore two motors. These motors will be used together to position the axle. This means there are two actuators on this one degree of freedom and the system is redundant. Theoretically, one motor could be used to pivot the wheel axle if the other motor should fail. However, in this situation, the mobility and robustness to disturbances comes into question.

efficiency

The concept of free pivot steering is a much more efficient system than tank steering. Since the wheel axles are rotated in the direction of travel, the wheels are never forced to slip laterally. This means that all motor power will be put into moving the vehicle forward instead of dragging the wheels.

mobility

The advantage of free pivot steering is the inherent efficiency of the system. However, the mobility of the rover is compromised by free pivot steering.

If an obstacle is encountered by one wheel, and this wheel is not able to overcome this obstacle, there is nothing to hold the axle in place. Also, since the axle is free to pivot, there is nothing to hold the wheel against the rock and produce the friction required to climb the rock.

An example of this is shown in figure 4.9 a). The rover is traveling straight as the left front wheel strikes a rock. The left front wheel is not able to climb this rock on its own, and a problem is encountered. In an effort to maintain the straight steering situation, the left wheel will speed up and try to climb the rock. The right wheel will slow down, and reverse directions in an attempt to straighten the front axle. However, the other drive wheels will continue to move the rover forward. Since the axles are free to pivot, the rear and middle drive wheels will not help the front axle overcome the rock. If the front wheels are not able to climb the obstacle, the front axle will rotate and the steering system will be disrupted, as shown in figure 4.9 b).

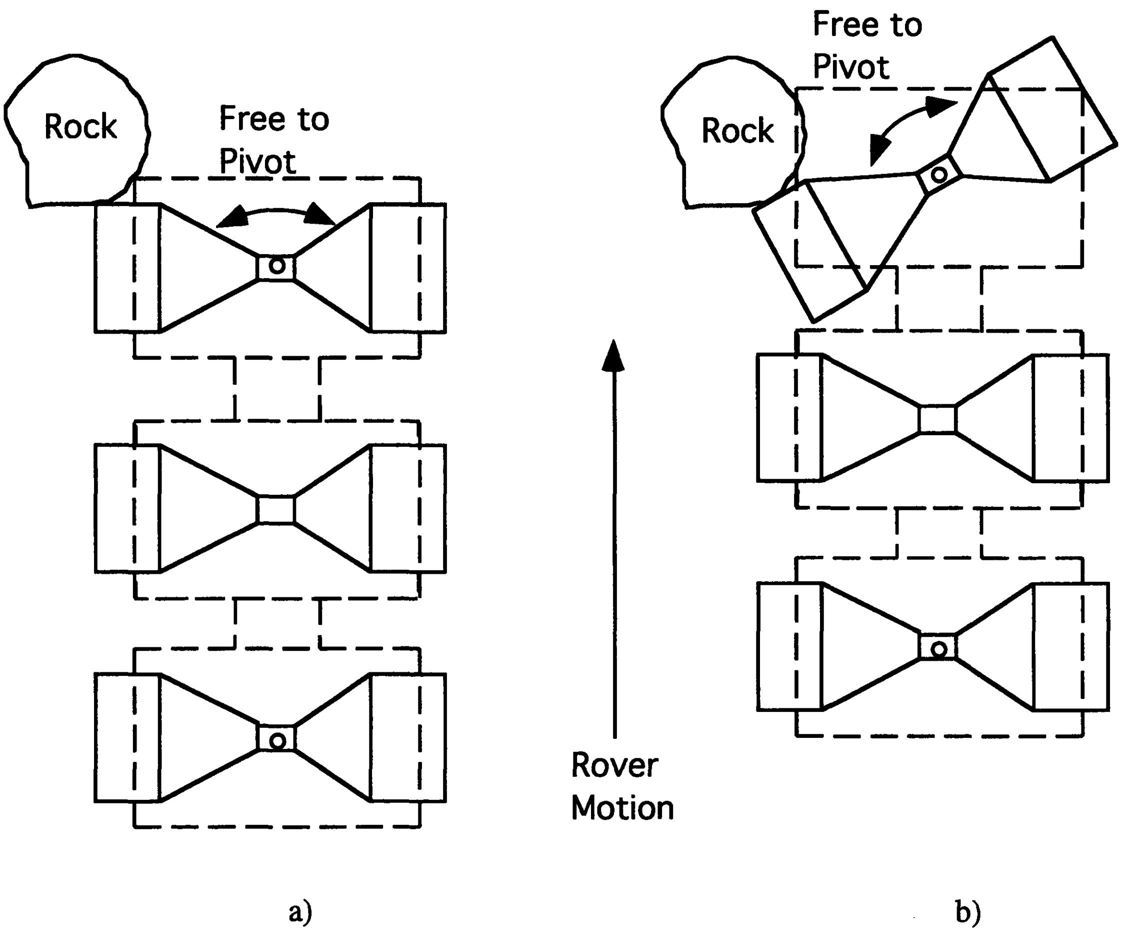


Figure 4.9: A Disturbance In Free Pivot Steering

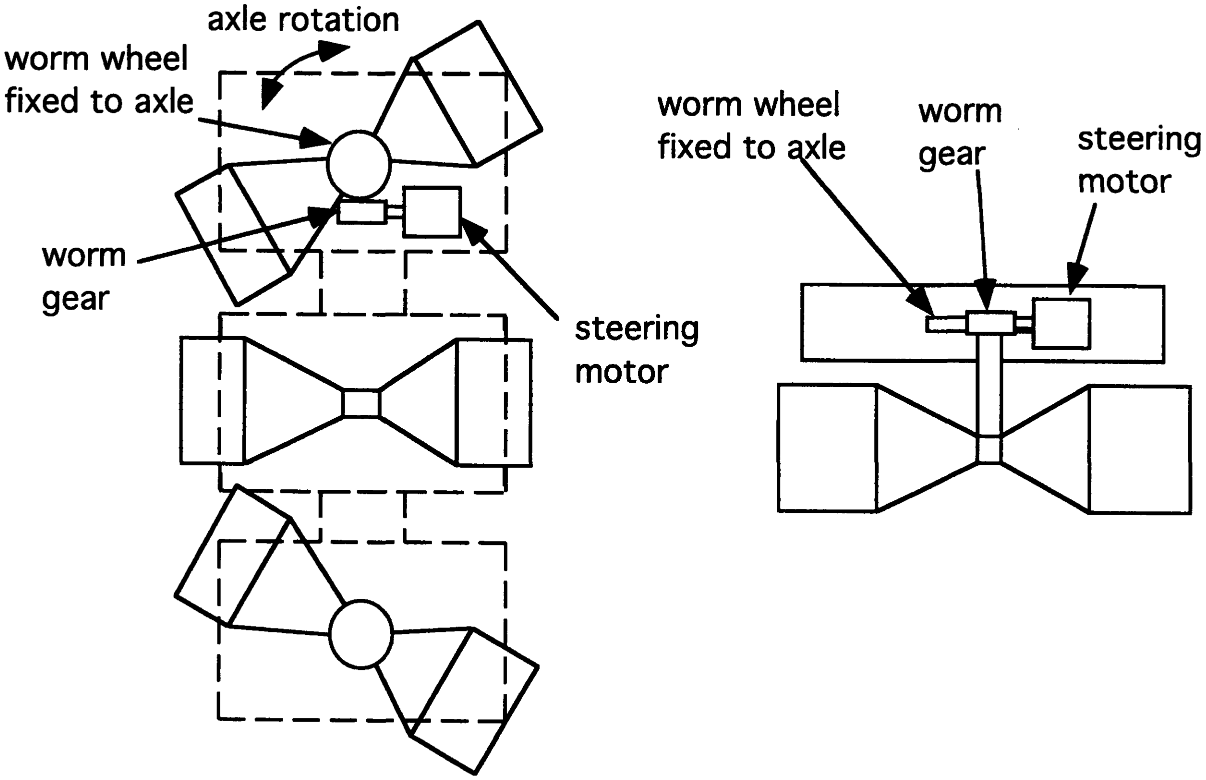
Normally, with a rigid axle, the forward motion provided by the other five wheels will help to push the front left wheel against and over the obstacle. Since the axle is free to pivot the forward motion provided by the other four drive wheels does not help the front left wheel climb the obstacle. This scenario defeats the purpose of having a six wheeled vehicle because the remaining wheels will not aid vehicle mobility.

Hybrid Steering

The mobility problems encountered with free pivot steering lead to the development of hybrid steering. It was desired to create a system where the vehicle axles could be pivoted using the power from the existing wheel drive motors, while being capable of holding the axle in place when subjected to disturbances. Hybrid steering combines the advantages of servo steering and free pivot steering while eliminating the drawbacks to these individual systems.

differential wheel speeds with worm following

Hybrid steering is very similar to free pivot steering in that the wheel drive motors, on opposite ends of the axle, are driven at different speeds to rotate the vehicle axle. In this steering concept a worm wheel is placed at the pivot point of the wheel axle. A worm gear engages this worm wheel and is powered by a separate steering motor. The torque required to rotate the vehicle axle is still provided by the wheel drive motors, but the worm gear follows the axle as it pivots as if it is providing the power. Once again, to turn left, the right wheel is run at a higher speed than the left, which produces an axle rotation. This time, this axle motion is followed by a worm gear system. A general picture of this system is seen in figure 4.10. This is an overly determined system since there are three motors connected to this one degree of freedom: one motor in each wheel and one motor on the shaft of the worm gear. The worm gear rotation must be coordinated with the rotation of the wheel axle created by the drive wheels. Coordinating the motion of these three motors creates a very interesting controls problem.



a) top view b) front view

Figure 4.10: Hybrid Steering

In this system, the worm gear provides no torque to rotate the wheel axle. The only torque the worm gear motor is required to provide is that which is required to overcome any friction in the system. In this sense the worm gear motor is not an actuator to rotate the axle, it merely follows the motion of the axle.

With the worm gear in place it is not possible to rotate the wheel axle without the worm gear being moved. This is a property inherent to the worm gear. Due to the high helix angle of the worm gear, the force transmitted from the worm wheel to the worm gear is primarily along the axis of the worm gear, not in the direction of rotation. This is the primary reason the worm gear was chosen for this application. As a force disturbance is introduced at the wheels it is absorbed mechanically as a reaction at the worm gear. Therefore the wheel axle will not rotate unless the worm gear allows it. This is illustrated in figure 4.11. The worm gear motor moves the worm gear to correspond with axle motion at all times, this means the axle is "locked" in place at all times and in any position.

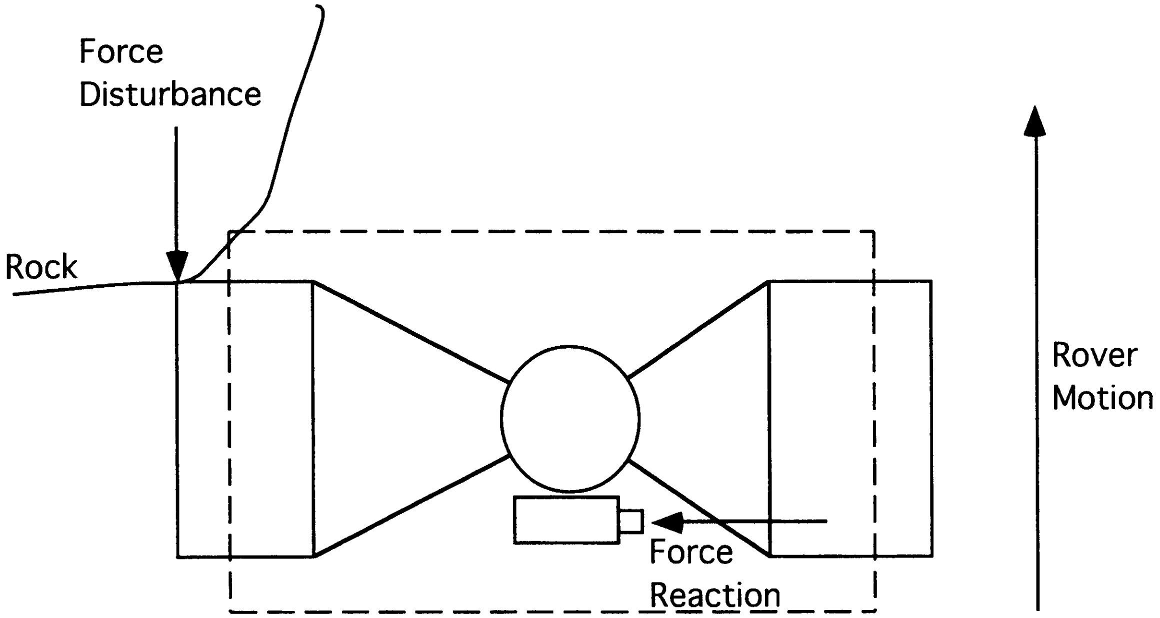


Figure 4.11: Hybrid Steering Force Disturbance

Overall, the worm gear motor does very little. It is only in motion when the wheel axles are being rotated, and only provides enough torque to overcome friction between the worm gear and worm wheel.

The obvious constraint in this design is that the worm gear must rotate at the correct speed to be coordinated with the axle rotation provided by the wheel drive motors. If that is not the case, the drive motors and the worm gear will work against one another. It is important to insure that the worm gear is never opposing the action of the wheel drive motors. If the worm gear is moving the wheel axle in the same direction as the wheel drive motors, the only torque the worm gear motor has to provide is enough to overcome the gearing friction.

There are distinct advantages to using a worm gear over other ways of preventing axle motion. A clutch could be used to hold the axle in place. This clutch could not be used while the wheel axle is turning without greatly complicating the system. This would make the axle susceptible to disturbances when the vehicle is steering. The advantage of hybrid steering is that the axle can be rotated by the wheel drive motors in the direction of a turn, and this axle is not susceptible to disturbances at the wheels. A disadvantage to this concept is that one steering motor is required at each axle to rotate the worm gear. Also, the worm gear motion must be coordinated with the drive wheels to allow correct steering motion making control difficult.

mobility

With the worm gear in place disturbances that are encountered as the wheels strike obstacles are not allowed to rotate the axle. Forces from climbing obstacles are transmitted through the worm gear and are absorbed mechanically by the vehicle structure. This protection is in place at all times, whether the vehicle is turning or not.

While the vehicle is in rough terrain, the wheels are always pointed in the direction of travel, this is an advantage in climbing in that the wheels always are oriented in the correct direction to climb over an obstacle. Since the axle is held solidly in place, the forward motion produced by the other five wheels will help to push a stuck wheel against and over an obstacle. This shows the great advantage of having a six wheeled flexible vehicle. These wheels and flexibility help to ensure that there will be good contact and good traction with the ground surface, which increase the rovers ability to climb obstacles

The vehicle axles are basically fixed in place by the worm gear providing a very high stiffness between the wheels and the vehicle structure. Another form of actuation, such as a geared servo motor with a linkage, would provide a spring stiffness as opposed to a rigid coupling. In this comparison the worm gear provides a mechanical rigidity, as opposed to a high current, high power electrical stiffness, relaxing motor requirements.

efficiency

Worm gears are not a highly efficient way to transmit large torque. However in this application the torque to rotate the wheel axles is provided by the wheel drive motors, allowing the worm gear power transmission to be very small. As mentioned before, the only torque required as input is the torque to overcome the friction between the worm wheel and the worm gear. However when a wheel disturbance produces a force at the worm gear, this friction is what prevents the worm gear from being back driven and the axle from rotating.

In this steering system the axles are rotated to the direction of the vehicle turn. This fact, together with the use of differential steering, makes the system very efficient in terms of reducing wheel slip. This is similar to free pivot steering but is quite different from tank steering, which requires inefficient wheel slip. This steering system takes the efficiency advantage of free pivot steering and combines it with the locked axle mobility advantage of tank steering.

Finally the worm gear motor can be quite small and the system can be constructed to fit in a small space below the vehicle platform. This promotes efficiency in packaging as well as in weight.

reliability

The hybrid system is an inherently reliable system. In the event of a wheel drive motor failure the particular axle can be actuated by the remaining drive motor. This will reduce the mobility performance of the overall system but should not effect the steering greatly. In the event of a worm gear motor failure that particular axle can simply utilize tank steering. Also, an additional motor could be placed on the worm gear shaft to allow for redundancy in this aspect of the system.

Although the worm gear concept introduces an amount of complexity into the steering system, it has many great advantages over other forms of steering. The additional gearing and bearings are always a possible point of failure, but this steering system does not introduce any obvious risks that jeopardize the mission.

Summary of Steering Concepts

Each of these steering systems has its own advantages as well as disadvantages. There are obviously trade-offs between the different aspects of each system. Figure 4.12 summarizes the steering system. Each system is compared relative to the others, with 1 being the worst and 4 the best.

	Electrical Efficiency	Mobility	Control Complexity	Size and Weight	Reliability
Ackerman	2	2	4	1	2
Tank	1	3	3	4	4
Free Pivot	4	1	2	3	1
Hybrid	3	4	1	2	3

Figure 4.12: Summary of Steering System

4.4 MITY-3 PLATFORM DESIGN

4.4.1 Initial Mechanical design

Overall vehicle design for the MITy-3 rover was done in the summer and fall of 1993. Initially the design utilized free pivot steering as the only means of steering the vehicle. The design utilizes the same basic structure as MITy-1 and MITy-2. The platforms were changed from plates to a frame support system. Mounted on the frame supports are larger instrument boxes, to allow for more internal space. Conical 6" diameter wheels were built from aluminum.

The rover was assembled and operating midway through the fall semester of 1993. A control system was then developed to steer the vehicle. The system was then tested to prove the differential wheel speed concept. The steering system performed very well on flat terrain, however problems were encountered when climbing obstacles.

lessons learned

Going into the construction of MITy-3 the questions pertaining to the mobility of a vehicle that uses free pivot steering were prevalent. As the vehicle went through initial tests it became clear that the free pivot steering would limit the vehicle's mobility. However, it was not clearly determined how much this limitation would be. Due to hardware problems some of the vehicle was redesigned. Since the vehicle was to undergo some design changes a new steering system was built to allow the use of a variety of steering concepts. This was done so that the value of each steering concept could be clearly assessed.

After the initial testing of MITy-3 it was clear that special attention had to be given to certain aspects of the design. For instance, the routing of the wires to provide power to the motors and receive feedback from the tachometers was critical. These wires needed to extend from the platform down to the wheels. This wiring had to allow for motion of the axles, and it was hoped that the wires could be completely enclosed in the vehicle structure. Also, the position of the wheel axle had to be measured using a potentiometer, the placement of this potentiometer, coupled with the wire routing, was of great importance.

4.4.2 Current Mechanical Design

The current steering design allows the rover to use tank steering, free pivot steering, and hybrid steering. The normal mode for steering the rover is hybrid steering. Tank steering can be accomplished by simply not rotating the worm gear, this locks the axles in place. To free pivot steer the vehicle the worm gear can be physically moved away from the worm wheel. This versatility will allow for three forms of steering to be evaluated.

A photograph of the MITy-3 rover can be seen in figure 4.13.

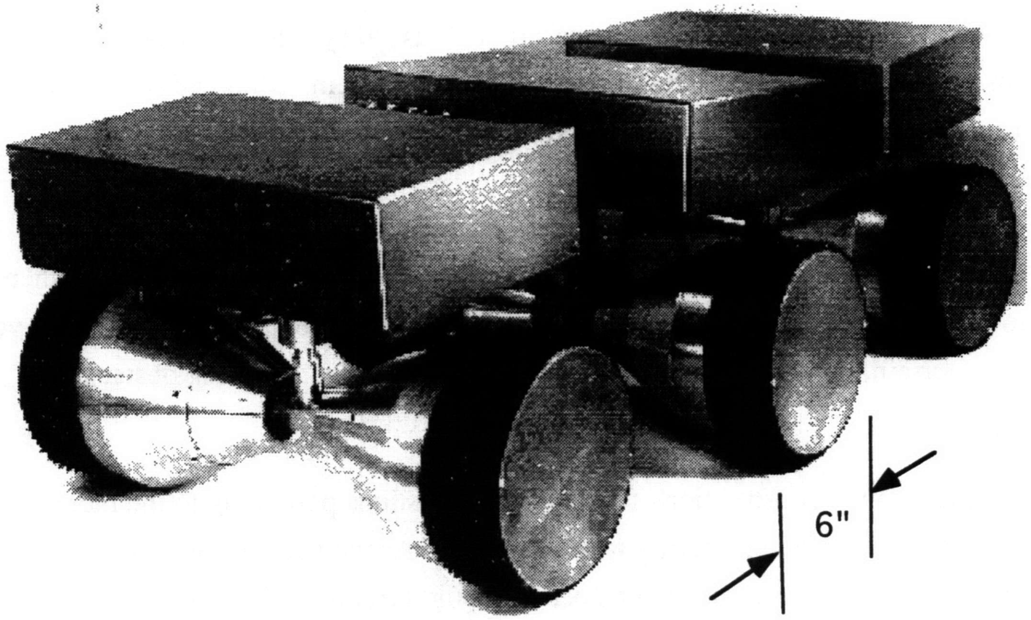


Figure 4.13: The MITy-3 Rover

In the initial design, the relative motion between the vehicle structure and the vehicle axle was at the height of the vehicle axle. It was decided to move this motion up to the height of the platform, this would allow the worm wheel to be mounted within the instrument box. A main shaft, fixed to the wheel axle, extended from the wheel axis upward into the instrument box. This shaft was supported by two ball bearings just underneath the instrument box. These bearings were separated by a 2" shoulder, to allow for support of non-axial loads place on the shaft. Such loads would be encountered as the vehicle strikes and climbs an obstacle. These main shaft bearings were then supported on the outer race by a bearing cup. This cup completely enclosed the bearings and mounted to the underside of the vehicle structure. Enclosing the bearings was desirable to protect them from debris. A schematic of this design is seen in figure 4.14.

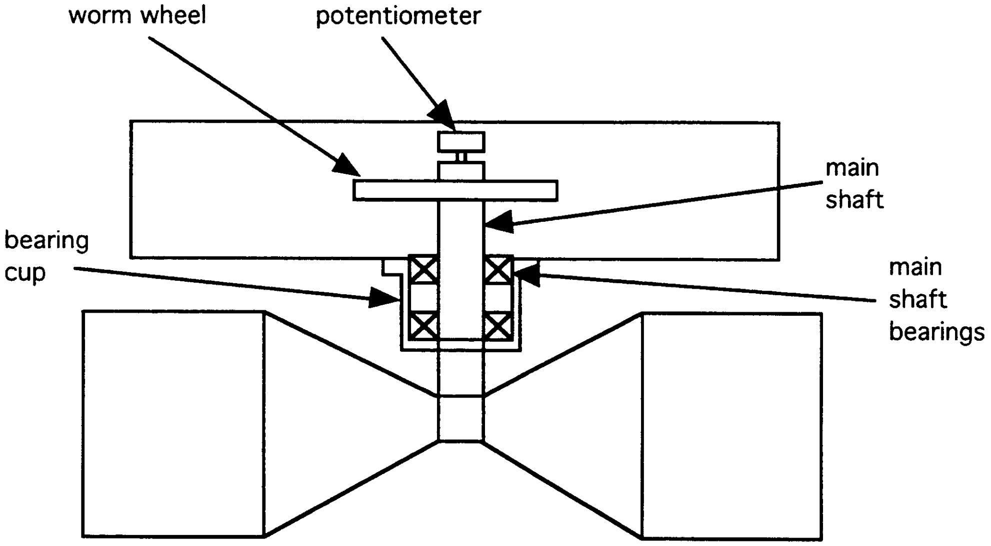


Figure 4.14: Current Mechanical Design

This main shaft then extended upward into the instrument box. Within the instrument box the shaft was again shouldered to support the worm wheel. Finally the main shaft was coupled with the potentiometer shaft to allow the potentiometer to measure the relative motion between the vehicle structure and the wheel axle.

A photograph showing this design is shown in figure 4.15.

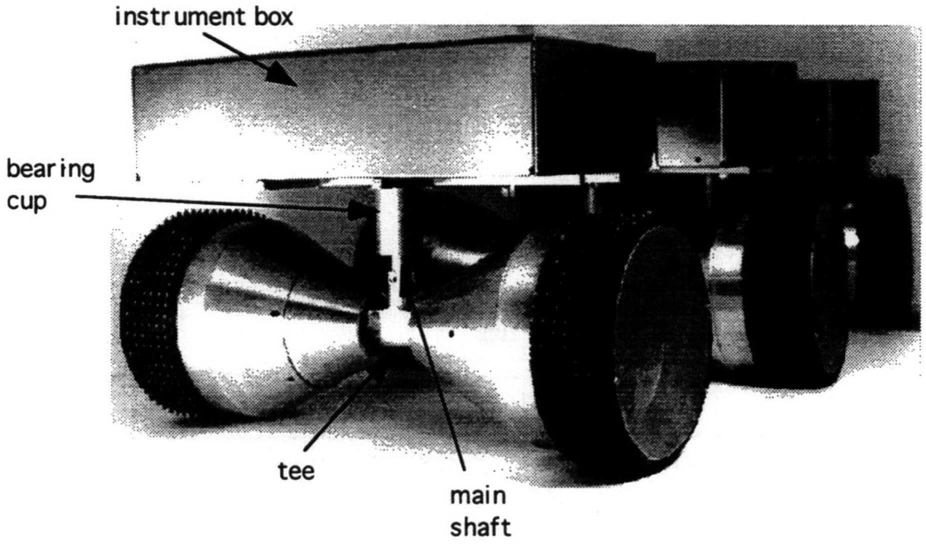


Figure 4.15: Photograph of Current Design

The motor/tachometer wires were routed through a hole drilled in the main shaft. The wires came together in a tee shaped piece fixed to the lower end of the shaft. The wires then traveled up through a hole drilled down the axis of the main shaft. Once the shaft entered the instrument box, the wires exited through a hole in the side of the main shaft. Here there would be relative motion between the wires fixed to the main shaft and the vehicle structure. To allow for this motion the wires were wrapped in a spiral around the main shaft. This would allow the main shaft to rotate with the wheel axle and the end of the spiral of wires to remain fixed to the vehicle structure. This is illustrated in figure 4.16. This idea is similar to a torsional spring used in a watch. This wire routing confined the wire motion to a small area beneath the worm wheel, this wire area was then enclosed to prevent entanglement.

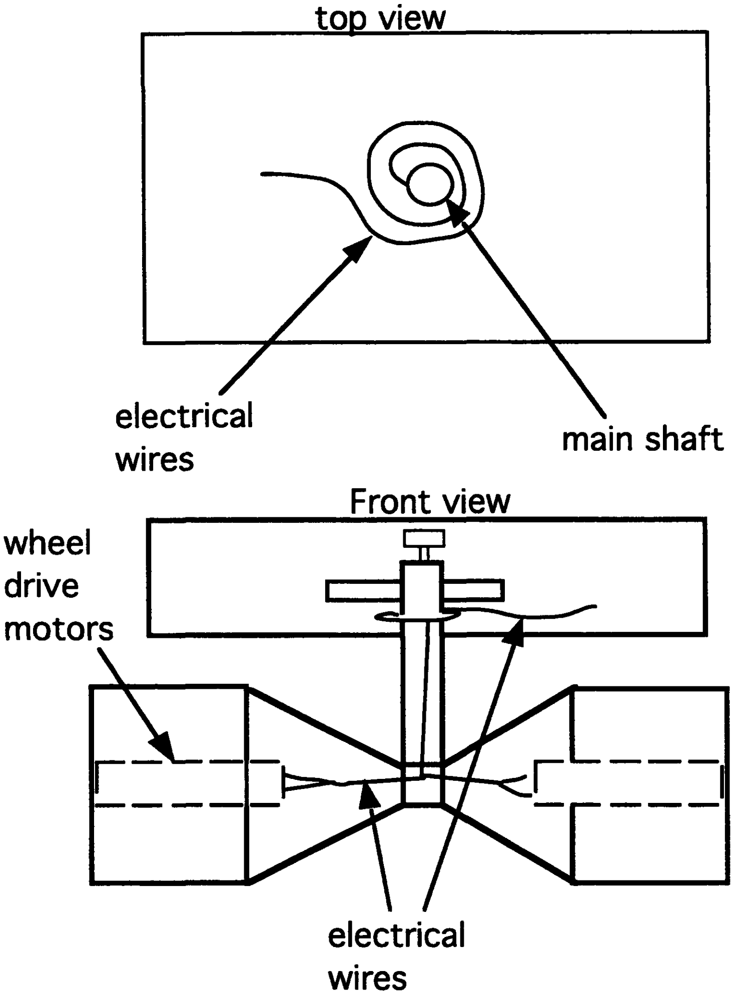


Figure 4.16: Wire Routing

The worm gear then engaged the worm wheel within the instrument box. The worm gear was mounted to a shaft which was supported at each end by bearings. These bearings and bearing mounts were designed to support the axial load seen by the worm shaft. This axial load was produced by force disturbances at the wheels, and this is where the reaction forces required to hold the wheel axle in place are produced. The worm gear shaft was then attached to a worm gear drive motor via a flexible coupler. The top view from within the instrument box is shown in figure 4.17.

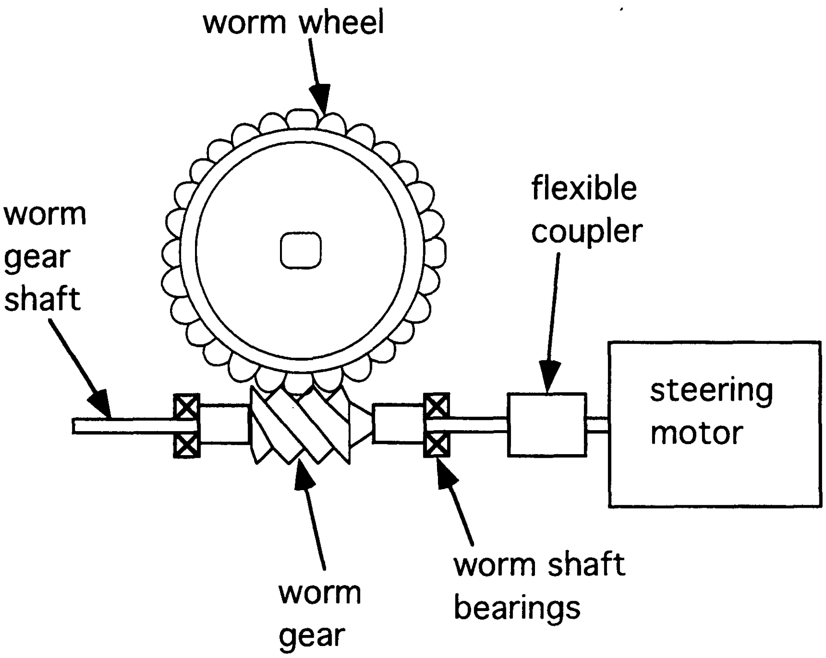


Figure 4.17: Worm gear train

A photograph of the worm gear system is shown in figure 4.18.

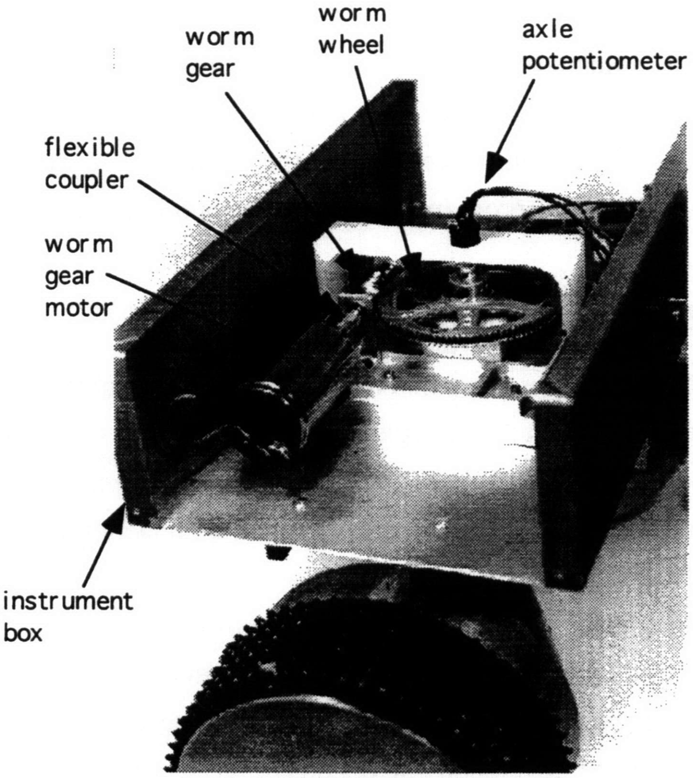


Figure 4.18: Photograph of worm gear arrangement

lessons learned

This design has performed well, to this date there have been no failures. The hybrid steering concept had a lot of unknowns going into the design. For instance, the magnitude of the frictional forces encountered between the worm gear and worm wheel, was not evident. Also, the axial load transmitted to the worm shaft from various wheel disturbance was not obvious, These forces are encountered as the rover crosses rough terrain and climbs obstacles and are not easy to quantify.

For these reasons the worm gear motor was oversized to ensure its ability to overcome friction in the system. Also, the worm wheel was oversized to reduce the frictional forces between the worm wheel and worm gear.

If this steering system proves successful in testing and a good feel for these parameters is gained, the entire steering system may be shrunk and placed below the rover's instrument box. This will save the valuable space within the box. The final system could be a very compact, low power, effective steering system.

4.5 CONTROLLER DESIGN

Once the vehicle became operational a control software had to be developed to operate the vehicle steering as well as control the vehicle speed. This control software used the existing architecture developed on the second rover prototype. This control software was written in C programming language and implemented on the ZILOG micro-processor.

4.5.1 Speed Control

Wheel drive motor speed had to be controlled to create the overall motion of the vehicle. This controller had to be able to maintain vehicle speed over completely unknown terrain, where it would encounter large disturbances.

Each of the six drive motors are equipped with tachometers. These tachometers provided the feedback signal for the control system.

Integral control was used to control overall vehicle speed. This eliminated the effect of any disturbances seen, such as rough terrain or friction. The response of this controller was adequate to maintain overall vehicle speed. The speed control system was very similar to the one developed and tested for the second rover prototype [1].

4.5.2 Steering Control

To steer the vehicle the speeds of the motor on the right side of the axle had to be controlled in coordination with the motor on the left side of the vehicle. This must be combined with the overall vehicle speed to accomplish steering.

The angular position of the wheel axle with respect to the vehicle structure is measured using a potentiometer. This potentiometer is the source of feedback used by the control system to steer the vehicle when using both worm gear steering and free pivot steering. The objective of the steering control system is to maintain the wheel axle at the commanded turning angle.

When the rover is using the hybrid steering system, the worm gear motor also needs to be coordinated with the motion of the wheel axle by the control software.

It was hopped that the speed of each wheel would not have to be closed loop controlled. This would require more processing time and more feedback. Instead, each motor is command based on the potentiometer reading. Initial testing has shown that this method is adequate, however work is in progress to see if closed loop control on all wheels will greatly increase performance.

Comands to the control software are input through the keypad interface with the Zilog microprocessor. The rover receives forward and reverese speed commands along with left and right steering commands.

Free pivot steering

In free pivot steering the relative speed between the left and the right wheels must be controlled to maintain steering attitude. To accomplish this a proportional derivative and integral control system was implemented. Proportional control was used to correct the axle position, derivative control was used to improve the transient response, and integral control was used to remove any disturbances seen at the rover wheels.

System Modeling

To develop an effective control system the rover steering system was mathematically modeled to estimate control gains for an effective control system. Since all aspects of the system could not be modeled, the model served as a general guideline for gain selection.

Because the physical system was already in existence, a test was conducted to determine the physical parameters of the real system. This test took the form of a step input to the motor wheels. To accomplish this the wheel axle was rotated to one side, then the motors were given a input voltage step. As the wheels responded to this step input the speed of the wheels were measured using the wheel tachometers and the Zilog microprocessor.

It was decided to test the motors to this step input while the vehicle was on the ground. This limited the amount of data that could be taken because of the limited motion of the wheel axle, however the wheels did have time to reach a steady state speed. The vehicle was tested while it was on the ground so that the test conditions would be identical to operating conditions. Performing the test in this way included effects such as vehicle weight and ground wheel interactions.

The system was modeled as a first order response, therefore the main system characteristic was the response time constant. This time constant varied slightly with the amplitude of the step input command so an average value was used. This variation in the system time constant was most likely due to unmodeled effects such as flexing of the structure and friction. The average wheel time constant was found to be 0.15 seconds.

This information was then transferred to the s domain and the system represented in a block diagram as seen in figure 4.19. The closed loop transfer function for the steering system and controller was then found, it is shown in equation 4.1.

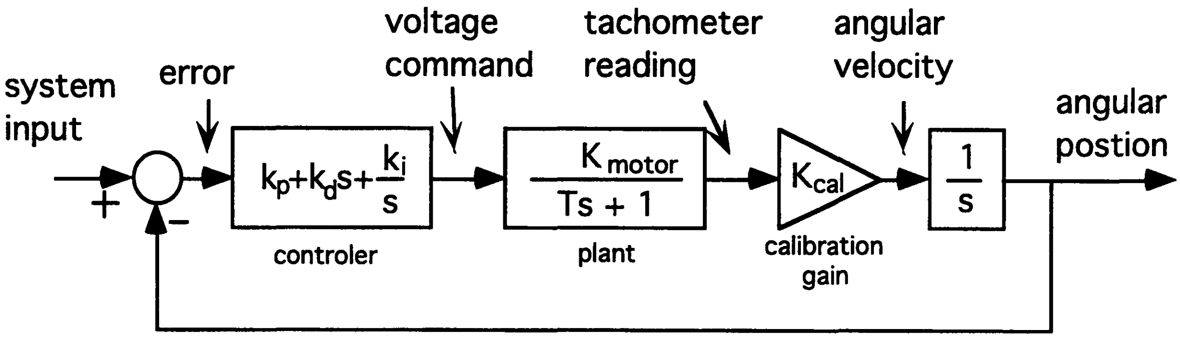


Figure 4.19: System Block Diagram Representation

Where k_p, k_d, and k_i represent the control system gains. K_{motor} represents a constant associated with the motor response, and T the motor time constant. K_{cal} is a constant used to convert units and calibration values.

$$TF_{\substack{closed\\loop}} = \frac{K_{motor}K_{cal}(k_d s^2 + k_p s + k_i)}{Ts^3 + (K_{motor}K_{cal}k_d + 1)s^2 + K_{motor}K_{cal}k_p s + K_{motor}K_{cal}k_i}$$

(equation 4.1)

This is a very simple model of the system. This model assumes that the system is completely linear and continuous. This does not include important factors such as friction and controller cycle rate. For these reasons this model is used as a guideline in gain selection.

Controller Performance

The feedback gains were than chosen to produce a performance corresponding to the chosen parameters. This was accomplished through a combination of simulation in matlab's simulink as well as tests on the actual system. The performance parameters used to characterize the response were the maximum percent overshoot and the system settling time. As the rover moves forward and then turns, the axle should adjust to the new steering angle quickly without large overshoot. The results of the simulation as well as actual data measured using the final control system is shown in figure 4.20.

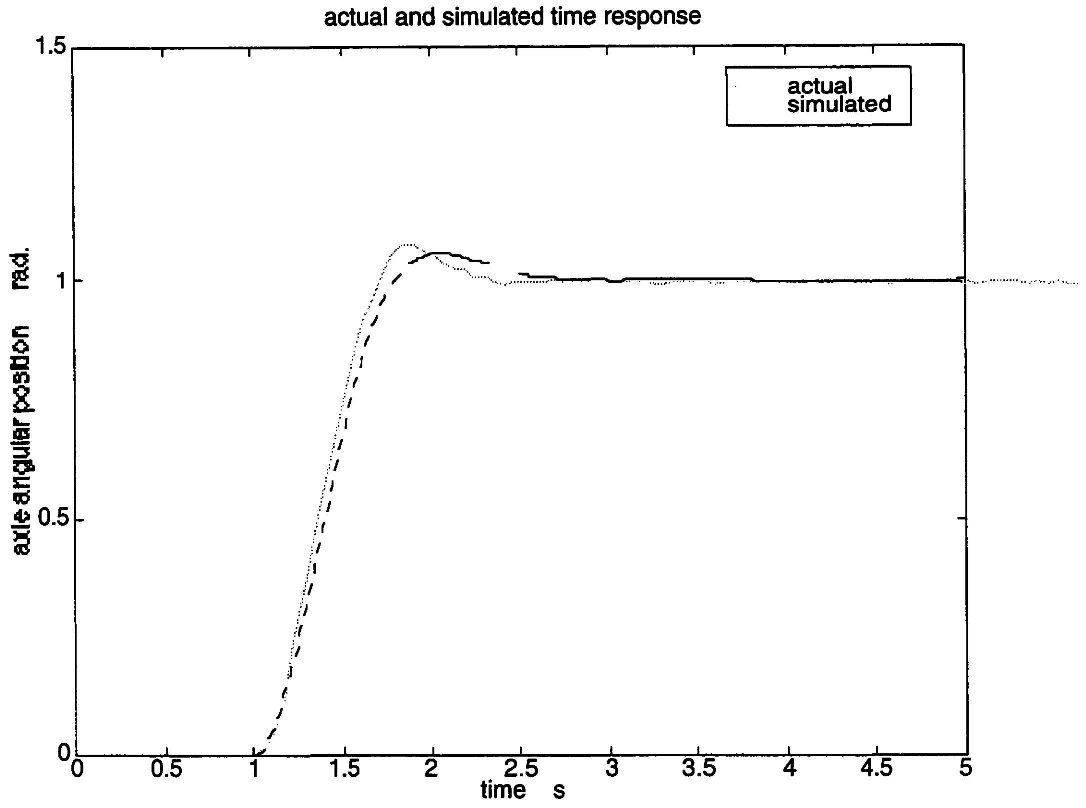


Figure 4.20: Actual and Simulated Step Response

The response of the control system to this input has approximatley 10% overshoot, .5 second rise time and a 1 second setteling time. This resulted in very good steering performance. The simulated and and actual time response have good correlation for a large input step. When the error is large the unnmodeled paramaters such as friction and nonlinearites are not as prevelent.

The controller implemented was discrete with an approximate cycle rate of 10 hz. Currently the steering and speed controller are the only tasks of the microprocessor. When the rover is fully operational much greater demand will be place on the processor. This 10 hz. cycle rate is the estimated cycle rate of the controller when the rover is fully operational. Steering performance was greatly degraded by slower cycle rates.

Other problems encountered in the controller design was the nonlinearites between voltage command and motor speed. Because of mechanical friction there is a significant voltage threshold below which there is no wheel motion. This threshold caused slight oscillation in axle position as the rover move forward at slow speeds. During testing this oscillation did not prove to be a problem.

Throughout development and testing problems were encountered with electrical noise in the potentiometer feedback. This noise also greatly effected controller performance. Derivative control was especially sensitive to this noise. With great effort the noise was reduced to an acceptable level before final testing.

It was also discovered that the rover power source also greatly effected controller performance. A low battery would produce a slower response than a fully charged one. This response was also quite different if an external power supply was used. The effects of the power source only effected speed of response and did not greatly degrade overall vehicle performance.

Tank Steering

In tank steering, the overall vehicle speed was controlled in the same manner as in free pivot steering.

To tank steer the speed of the wheels on the right side of the vehicle must be controlled with respect the wheels on the left side of the vehicle to rotate the vehicle. Commands were input into the system in terms of this speed differential. The larger the relative speed on one side with respect to the other, the sharper the turn.

To maintain this speed differential PI control was utilized. During testing of this controller it was discovered that the vehicle did not have the power requied to tank steer. In order to turn the rover the front and rear wheels must move in a direction different than the direction in which the wheel would normally roll. This situation is exaggerated by the high length to width ratio of the rover. Also, much of the vehicle weight is above the front and rear platforms increasing the friction between the ground and wheels. This length to width ratio and weight distribution prevented the rover from tank steering.

When the rover attempted to turn in place, the motors would reach full power and stall. The rover was just capable of turning if the rover was moving forward while trying to turn. This type of turning consumed a large amount of power and accuracy was very poor.

Hybrid Steering

Control of hybrid steering was very similar to that of free pivot steering. The control system is still operating on the same plant as in free pivot steering. The requirement for this to work is that the worm gear is controlled to follow the motion of the wheel axle.

It is extremely important to note that in this steering concept, three individual motors operate on the same degree of freedom. Each of the two wheel motors as well as the worm gear motor move as to rotate the wheel axle. This is a very redundant system.

Controller Performance

To control the steering angle, the wheels were commanded in exactly the same manner as they were commanded in free pivot steering. The response of the drive wheels was slowed slightly to eliminate any overshoot in the drive motor response. The requirement placed on the worm gear motor was that its response would be faster then, so as not to conflict with, the axle motion. It is important to note once again that all torque required to rotate the wheel axle is provided by the wheel motors. The worm gear motor merely follows this motion.

The worm gear was controlled with proportional control. Once again the response of this motor must be fast enough stay ahead of the wheel axle. It was found that very little torque was required to move the worm gear. The response of the system was marginally slower than free pivot steering and was much less susceptible to disturbances with little to no steady state error.

4.6 STEERING AND MOBILITY EVALUATION

4.6.1 Criteria

With each of the possible steering systems developed for MITy-3, criteria had to be set up to decide the best steering method. The development of a new steering system was brought on by the use of conical wheels. Conical wheels were used to help increase overall vehicle mobility.

For this reason, the steering system must be partially evaluated based on its effects on vehicle mobility. If the advantages of conical wheels are not grater than the costs associated with the new steering system, then the entire design must be reevaluated.

The steering systems were evaluated on the basis of steering ability, mobility, reliability and efficiency. Each criteria playing an important role in the decision on steering system implementation.

steering ability

Each steering system was fully developed to determine its effectiveness in steering the vehicle. The basic question asked here is can the system effectively steer the rover. This includes steering in all situations. One system may operate better on flat terrain than on rough terrain and so on. One system may be capable of turning the vehicle in rough terrain while other systems cannot. Another guideline in this evaluations will be the limits on turning radius produced by the steering system.

To evaluate the steering ability the rover will need to drive through hazardous terrain while steering. This was tested by operating the rover first on a hard flat surface and then in deep uneven sand. In each of these environments the rover was driven over obstacle while steering.

mobility

The steering system used can greatly effect overall vehicle mobility. To decide between different steering systems each systems effects on mobility must be considered.

To evaluate each system the rover will need to be driven through difficult environments. This environments will include rough terrain, and obstacle climbing. The use of step climbing as a mobility performance measure is a good means of comparison.

reliability

System reliability is of extreme importance in rover steering. The rover must be able to tolerate different types of failures while still maintaining maneuverability. To evaluate the reliability of the different steering systems the rovers were driven with a motor disabled. This motor was not powered, however it was allowed to turn. With the disable wheel the rover was driven over different obstacles.

efficiency

The efficiency of the steering system is also very important. By the nature of the rover mission, maneuvering in tight spots is inherent and efficient steering is a must.

4.6.2 Tests Results

steering test results

Hard Surfaces

Both free pivot steering and hybrid steering were capable of steering the rover. Free pivot steering proved to be more susceptible to disturbances then hybrid steering.

While operating on a hard flat surface both types of steering were capable of maneuvering the vehicle consistently. While using free pivot steering slight oscillations of the axle position were seen as the vehicle moved at slow speeds. The effects of these oscillations on steering performance was not significant. At high speeds (≈30 "/sec.) both types of steering suffered. This is because the wheels reached full speed and were not capable of producing the required speed differential. This was not a problem at the rover operating speed of ≈12 "/sec.

Both hybrid steering and free pivot steering are capable of a zero truning raduis but it was found that a truning radius of 12"-18" was practical for both types of steering. This is an improvement over previous MITy steering systems.

rough terrain

While steering in deep sand steering performance was slightly slowed but not greatly effected. The unevenness of the sand effected free pivot steering more than hybrid steering. While free pivot steering the axle would bounce back and forth more than on a hard flat surface but this bouncing did not effect overall steering performance. No difference was seen in hybrid steering.

effects of disturbances

While steering in the face of disturbances hybrid steering performed very well. There was no change noted when the rover attempted to turn while climbing obstacles. This performance was much better than expected. The rover was driven in the deep sand while climbing 2" obstacles and had no trouble turning with obstacles of this size.

Free pivot steering was effected by disturbances. Steering performance was degraded when the rover attempted to steer while climbing 2" obstacle in deep sand. Often the obstacle would change the orientation of the axle and the rover would not turn in the correct direction. This was primarily a traction problem. No great stability problem was ever encountered during testing but steering performance was sacrificed.

mobility test results

The mobility of the rover was tested on both a hard surface and in deep sand. Both hybrid and free pivot steering were evaluated. To test the rover's mobility the was driven over different obstacles. On the flat surface the rover attempted to climb a step of various heights in different situations. While in the sand the rover was driven over 2" obstacles in different attitudes.

It was discovered during testing that the spring steel rods connecting the rover platforms are too stiff for the current rover weight. Often the front wheels would contact an obstacle then as the rear wheels drove forward the middle platform would be lifted and the middle wheels would loose traction. Another problem seen during testing was asociated with the conical wheels themselves. The current conical wheels are over the mass limit placed on them by the system requirments [4]. This also severly degraded overall vehicle mobility.

step climbing

Step climbing test were conducted on the hard flat surface. When the rover approaches a step directly it is capable of climbing a 5" step. This does not depend what type of steering is being used. This is limited by the stiffness of the spring steel. Generally the rover could not climb larger obstacles because the middle wheels would lose contact with the ground as discussed earlier. When the rover approaches a step at an angle the differences in the two different types of steering becomes evident. Also, the steering system made a difference if only one wheel struck the step.

Using hybrid steering the step climbing ability of the rover was not compromised. If the rover approached the step at an angle it was capable of climbing a 4" obstacle. If only one wheel hit the step the rover was also capable of climbing a 5" obstacle and a 4" obstacle consistently.

When using free pivot steering the step climbing ability of the rover is slightly reduced. If the rover approached the step at an angle it was able to surmount a 2" obstacle. When the rover struck an obstacle with just one wheel it was also able to climb a two inch obstacle consistently.

In both free pivot and hybrid steering the lack of traction was the limiting factor in step climbing.

motor disabled

To test the reliability of the steering system the rover was driven over step obstacles with one motor disabled. The rover approached the step so that only the unpowered wheel struck the step. When the rover was using free pivot steering it could not climb a 1" obstacle with a disabled wheel. Using hybrid steering the rover could still climb a step of three inches. This distance corresponds to half wheel height.

A summary of the step climbing ability of the rover is seen in figure 4.21.

	Straight approach	angled approach	one wheel strikes step	one wheel disabled
Free Pivot	4"	2"	2"	<1"
Hybrid	4"	4"	4"	3"

Figure 4.21: Summary of Step Climbing Test

rough terrain

When the mobility of the rover was tested in rough terrain both steering system performed well. The use of conical wheels proved to be a great success. In this stage of testing it was not possible to get the rover high centered even when attempts were made to do just that. This is a great increase in mobility performance.

Both free pivot and hybrid steering were capable of climbing two inch obstacles consistently. The only difference was seen in that the direction of the rover could be more easily changed by an obstacle while free pivot steering. When using free pivot steering the wheels would strike the obstacle and attempt to climb them. As one wheel gained enough traction it would climb the obstacle. Since one wheel made it over the obstacle the axle would twist and the rover would change direction. After one wheel has climbed the obstacle it would pull the second wheel over and the axle would correct itself. This did not produce a great mobility problem but did affect the direction of travel of the rover.

efficiency test results

The electrical efficiency of the each type of steering was not measured directly. The important thing that discovered was that the rover was not capable of tank steering. This means that the efficiency of this steering system was extremely poor. It is hoped to measure the electrical efficiency of the other two types of steering directly in the near future.

4.6.3 Results

Great success has been seen in the initial testing of the conical wheel design. It does appear as if mobility and reliability has been increased by eliminating the dead zone between the rover wheels. It is important to note that this first round of testing is not exhaustive and more work will be required to fully quantify these steering and mobility systems. However the initial testing of the MITy-3 rover does show some distinct differences between the steering systems. First, the inherent inefficiency of tank steering eliminates this as a possible steering system. Second, both free pivot and hybrid steering perform well as steering systems. Third hybrid steering corresponds to good mobility while mobility is slightly sacrificed with free pivot steering. Fourth hybrid steering is more mechanically complicated (an added motor). The results of the steering system evaluation are shown in figure 4.22.

	Efficiency	Mobility	Complexity	Steering
Free Pivot	good	fair	good	good
Hybrid	good	good	fair	good
Tank	poor	----	good	poor

Figure 4.22: Steering System Summary

SCIENTIFIC INSTRUMENT DEPLOYMENT MECHANISM
CHAPTER 5

5.1 MOTIVATION FOR DEPLOYMENT MECHANISM DEVELOPMENT

While designing a platform, such as a MITy rover, the final purpose of this platform must always be kept in mind. The prototype rovers built to date have focused on the problems associated with building an autonomous vehicle to travel on a planetary surface. However, the intention of this rover is to return scientific data. Accomplishing this final task requires the rover to be capable of more then traveling around. The rover must also be capable of transporting and utilizing scientific instruments, then returning their data to a ground station on earth.

One of the primary scientific tools of the rover will be the video camera. The rover will utilize this instrument to conduct photoreconosence of the surface. A camera for this purpose has been employed on the current micro-rover prototypes. Other suggested scientific instruments include an x-ray spectrometer or seismometers. The rover's job will be to transport these instruments to various locations, and allow them to gather the desired data.

A seismometer is a device used to characterize the seismic activity at that location of the planet's surface. The rover would need to remove the seismometer from a storage area on board and place it on the ground surface. The spectrometer is a device used to determine the chemical composition of the ground surface or a rock surface. To accomplish this the seismometer must be held against the ground surface or the rock for an extended period of time. A given rover mission would probably be dedicated to gathering one type of data, and equipped with one of these types of instruments.

To this end, a device is needed to deploy such scientific experiments. This device will need to transport the experiments from a stowed position on the rover to the operating position for the instrument. To fulfill this requirement the design and analysis of a mechanism to deploy one of these experiments, the Alpha-Proton X-ray Spectrometer (APXS), was undertaken.

5.2 INSTRUMENT DESCRIPTION

The APXS instrument will be used to determine the physical characteristics of the rocks and soil at different locations during the mission. Similar instruments have been utilized on previous Surveyor missions, as well as the Soviet Union's Phobos probes.

This instrument is being designed and built for use on a mission to Mars in 1994 as well as future Pathfinder missions. The spectrometer emits alpha-particles which are scattered by the target material. These scattered alpha-particles are then measured by an alpha-spectrometer. The energy of these scattered particles is a function of the mass of the target atoms, and this information can be used to determine the chemical composition of the target material [17].

The physical shape of the spectrometer itself can be approximated by a cylinder. The diameter of the spectrometer is 2" (52 mm) with a total length of 2.5" (63 mm). The detector head has a length of .9 (23 mm) and must be held approximately 1.6" (40 mm) from the target material, this is accomplished by a 1.6" spacer. The detector head and spacer comprise the total length of the instrument. The spectrometer will have an approximate mass of 1.5 lbs. (.7 kg), and consume an average of .8 watts. The operation time of the spectrometer is around 11 hours, this means that the instrument will need to be held in place for this extended period of time [9].

This spectrometer was designed at the University of Chicago and is being built for the Jet Propulsion Laboratory.

5.3 DESIGN CONSIDERATIONS

This design of a mechanism to deploy the spectrometer has some very distinct design constraints. Mass of the deployment mechanism is premium. This device has to be launched into space, and must be carried by the rover, for these reasons a light deployment mechanism is desired. Minimizing the volume required for the deployment mechanism was also an objective since space on board the rover is quite limited. Power is also a premium on the rover platform, therefore electrical power required to deploy the mechanism was considered. As a general guideline, focus was placed on mechanical simplicity. The mission scenario requires high reliability, therefore a simple device is more desirable then a complex one. The deployment mechanism will need to operate in the harsh Martian environment. Things like dust contamination and temperature variations well be significant.

Time spent deploying the spectrometer, as compared to the time of spectrometer operation and rover travel time, will be vary short. For this reason, a high speed deployment is not at all critical.

Another fact that must be noted is that the mass of the spectrometer is significant when compared to the mass of the rover. Also, the frame of the vehicle is very flexible. Considering these factors make overall vehicle stability a concern. For these reasons it is desired to keep the center of mass of the entire vehicle, including the spectrometer, as low as possible. Similarly the lack of a solid base for the deployment mechanism requires it to be adaptable to different platform attitudes.

Finally the spectrometer will need to be held against a rock and against the ground, for a variety of different measurements. Because the rover is traversing unknown terrain, the exact attitude of the rover with respect to the rock will not be well known. Similarly, the exact shape of the rock is also not certain. These two factors require the deployment mechanism to be adaptable to different situations.

5.4 MECHANISM GEOMETRY

Many different designs were considered to accomplish this task. Initially, the idea was to build a sophisticated robotic manipulator that could accomplish many tasks including the deployment of scientific experiments. It was decided that these tasks could be better accomplished through simple, reliable, individual mechanisms.

Once this was decided the design concentrated on a simple deployment mechanism for the spectrometer. It was decided that the spectrometer would be stowed on the rear platform of the rover and deployed behind the rover.

The first design considered was a one degree of freedom linkage. This linkage would be constructed to move the spectrometer from the stowed position to a horizontal position behind the rover. When the linkage was further rotated the spectrometer would be held vertically against the ground. This concept would only require one active joint, therefore only one motor. This is very simple, however, success in positioning would require the ground to be reasonably level, and the rocks to be of the correct height and attitude. Considering these factors this design is inadequate. It is expected that there will be great discrepancies in the deployed position of the instrument.

Mechanisms with more degrees of freedom were then considered. It was thought that the task could be accomplished using two degrees of freedom. The use of this second degree of freedom would greatly enhance the versatility in spectrometer positioning. Different mechanism geometrys were examined to determine if two degrees of freedom were adequate, and the final design was formulated.

In this design, the spectrometer itself would make up the second link of the mechanism. Figure 5.1 shows the basic design concept. The spectrometer is pictured in both the stowed and deployed position.

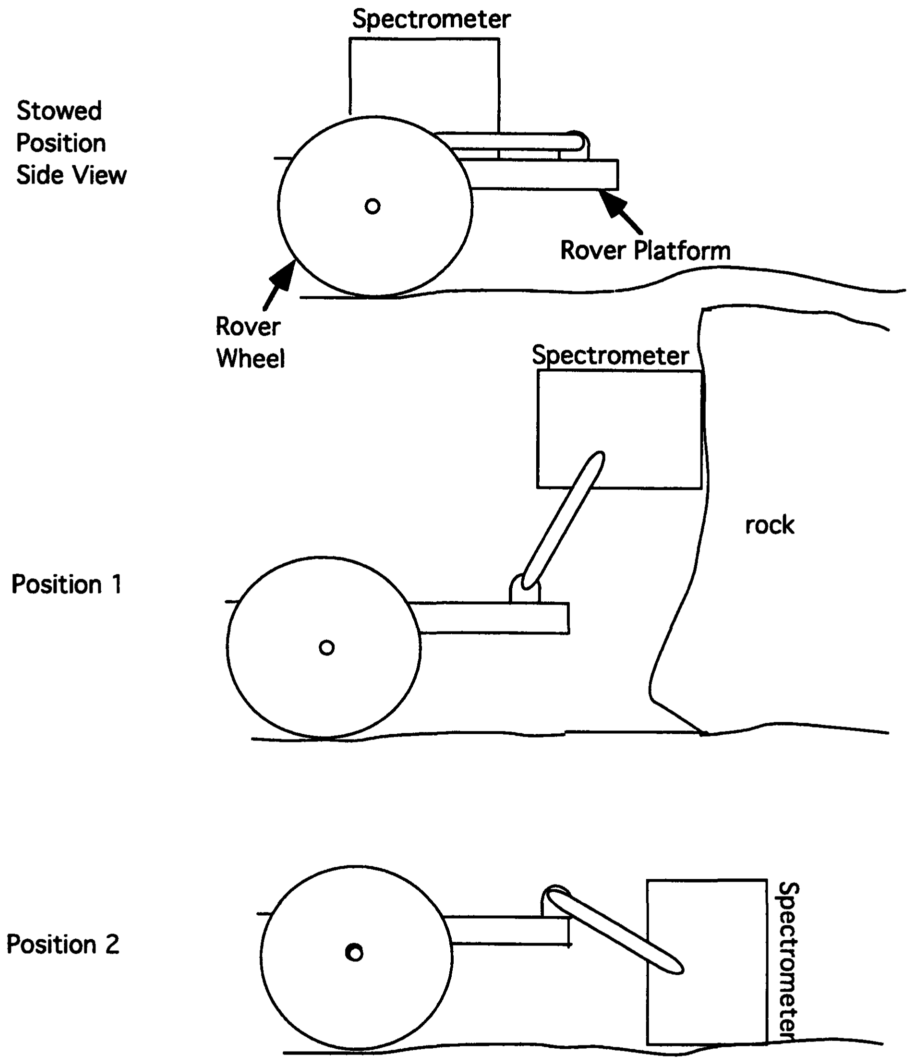


Figure 5.1: Basic Mechanism Concept

With a second degree of freedom in the mechanism, the exact position of the rover with respect to the target is not as critical. Also, this second degree of freedom can compensate for the deflection of the rear rover platform.

In actuality the rover itself will act as another degree of freedom of this mechanism. Since the mechanism is attached to the rear of the vehicle, motion of the vehicle will produce motion of the mechanism. The rover will act as a prismatic joint at the base of the manipulator. Therefore, this will actually be a three degree of freedom manipulator.

As an early step in the design process, a wooden model was constructed to demonstrate the concept and to determine the rough physical size of the mechanism.

5.5 MECHANICAL DESIGN ANALYSIS

5.5.1 Kinematic Analysis

The first step in analyzing this design was to perform a kinematics analysis. The mechanism was evaluated as a three degree of freedom planar robot with one prismatic joint and two revolute joints as seen in figure 5.2.

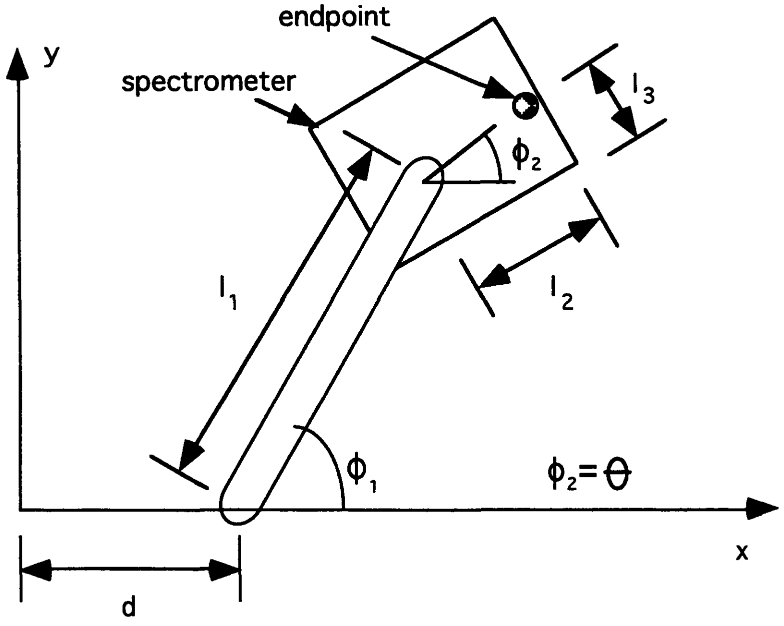


Figure 5.2: Definition of Coordinates

A Jacobean matrix was formulated that related displacement of the joint coordinates (q) to endpoint displacements measured in an inertial ground frame (p).

$$\delta p = J\ \delta q \qquad \text{(equation 5.1)}$$

$$\delta q = \begin{bmatrix} \delta d \\ \delta\phi_1 \\ \delta\phi_2 \end{bmatrix}; \delta p = \begin{bmatrix} \delta x \\ \delta y \\ \delta\theta \end{bmatrix}; J = \begin{bmatrix} 1 & -l_1 \sin\phi_1 & -l_2 \sin\phi_2 - l_3 \cos\phi_2 \\ 0 & l_1 \cos\phi_2 & l_2 \cos\phi_2 - l_3 \sin\phi_2 \\ 0 & 0 & 1 \end{bmatrix}$$

With this Jacobean, endpoint forces (F) could be translated into joint level torque's (T) in a static analysis. This information was useful in estimating motor size and gearing requirements. The joint torque as a function of angular position were calculated using a simple computer program, and these values were used in motor selection.

Since the deployment speed will be very slow, a dynamic analysis of the mechanism structure was not relevant.

5.5.2 Positioning of the Spectrometer

Positioning the rover and spectrometer with respect to the target was a large issue in this design. The fact that this target is not well known raises much difficulty in the positioning of the spectrometer. It is desired to place the base of the spectrometer against the target with the axis of the instrument normal to the surface of the target. The specifications of the spectrometer require contact with the surface and no more than a 20° angular error in this positioning [9].

The uncertainty of target shape and position requires the device to "comply" to the surface of the target. Also the rover platform does not provide a rigid base for deployment. Flexibility in the rover will contribute to the difficulties of accurate positioning. To elevate this difficulty many things were considered, the following sections define this problem more clearly then consider possible solutions.

Task Definition

In order to accomplish the task of placing the spectrometer against a target, a successful strategy must be developed. The rover will bring the spectrometer into the proximity of the target. Then the deployment mechanism will need to accomplish the final positioning.

The proposed mission scenario requires the positioning of the spectrometer to be done autonomously. At the beginning of a mission day, a video image of the terrain ahead of the rover will be sent to earth. From this image mission planners will choose an area, or rock, of interest that the rover will try to examine using the spectrometer. The general location of this area of interest will be ascertained from the picture and this information will be sent to the rover. It will then be the rovers job to traverse the terrain between itself and the target. Once it has arrived it will need to identify the specific spectrometer target. After locating this target the rover must position itself next to the target and begin to deploy the mechanism.

Once the rover has transported the deployment mechanism close to the target, it is the job of the deployment mechanism to place the instrument against the target. Since the physical shape and size of the target is unknown, and the exact location of the target with respect to the deployment mechanism is also unknown, final instrument positioning is not a trivial task. To make up for these unknowns the deployment mechanism will have to be capable of adapting to many different situations.

The spectrometer will approach the target at an unknown angle. As the spectrometer first touches the target, a reaction force will be developed. It is desirable for this reaction force to produce a corrective motion and thereby aid in the alignment of the spectrometer.

A useful way to view this situation is to picture this corrective force as a moment applied to the spectrometer about the instrument's "compliance center". The compliance center is defined as a special point on a non-rigidly mounted body. If the line of action of a force applied to the body passes through the compliance center only translation of that body will be produced, no rotation. If a force is applied that does not pass through the compliance center a rotation of the body will be produced about the compliance center [18].

Figure 5.3 shows the possible scenarios the spectrometer will encounter when it first contacts the target. Also shown are the desired motions required to align the spectrometer. These situations dictate a desired location for the compliance center. The final picture of figure 5.3 shows this location.

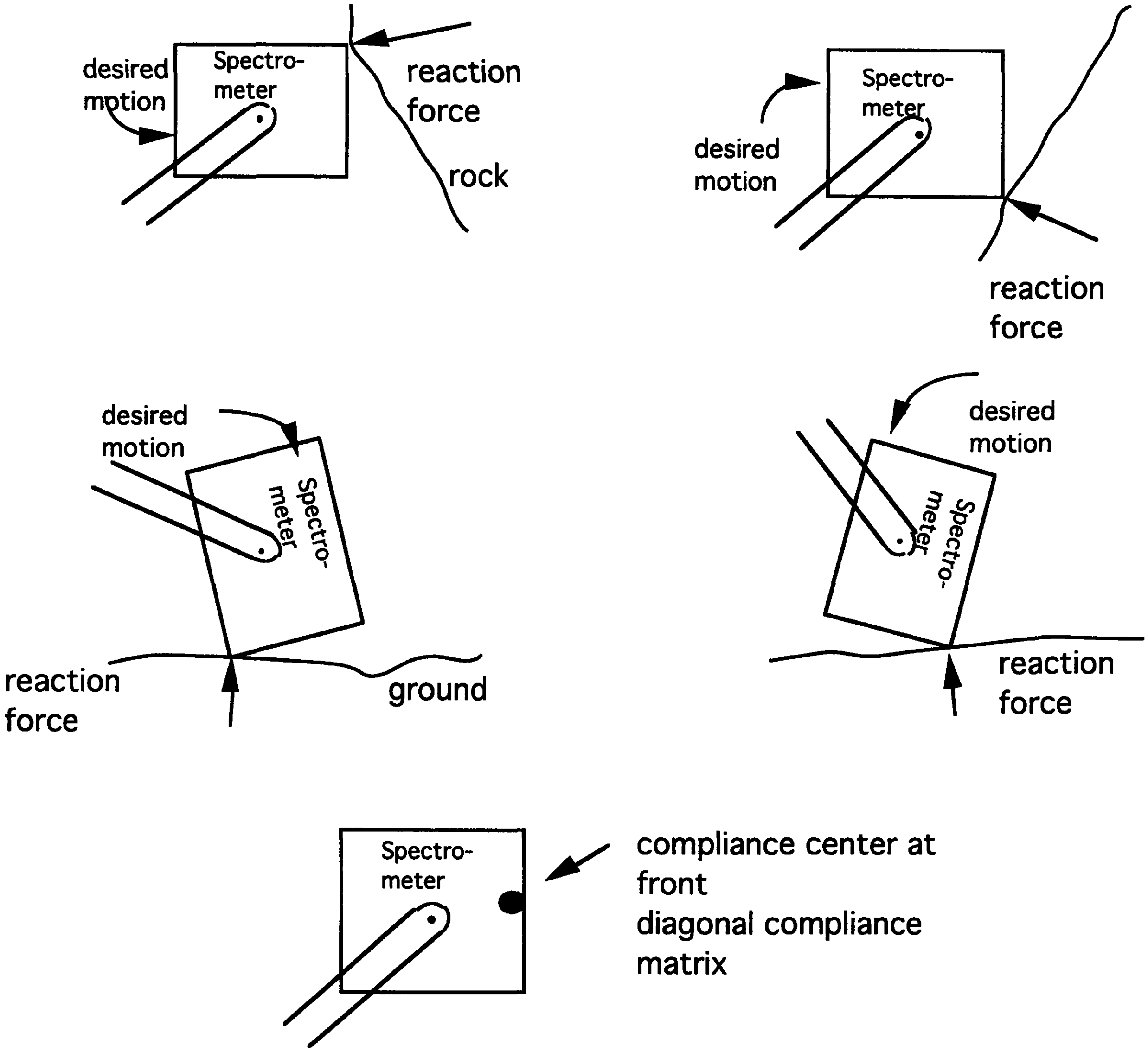


Figure 5.3: Spectrometer Positioning

Active Servo Compliance

One method to produce this desired compliance is through the use of the joint actuators. Active compliance involves the stiffness in the rotational joints of the mechanism produced by the drive motors within these joints. Stiffness, damping, and impedance can all be provided by the joint servos.

Initially the idea was to implement active servo compliance to adjust the position of the experiment. The problem was formulated and solved. A position for the compliance was chosen and the magnitude of the compliance at this point was assigned.

This compliance matrix was then transferred to the endpoint of the deployment mechanism. Finally this compliance was transferred to the joint actuators of the mechanism. The joint level feedback position gains are proportional to the joint level compliance. From this information a controller can be designed. The joint level compliance was given by:

$$C_q = J^{-1} J_c^{-1} C_{p'} J_c^{-T} J^{-T} \qquad \text{(equation 5.2)}$$

$$K_p \alpha C_q$$

J_c=Jacobian that transferees endpoint coordinates to compliance center coordinates
J=Jacobian that transfers joint coordinates to endpoint coordinates
C_q=joint level compliance matrix
$C_{p'}$=compliance matrix at compliance center (diagonal)
K_p=joint level feedback position gains

Advantages and Disadvantages of Active Compliance

Active compliance can be easily adapted to many applications by just changing the feedback gains. However this type of compliance requires a lot of computation therefore it is often slow in response, or requires a quick processor, which is not available in this application.

The major problem with this method of compliance is the effect of friction within the mechanism. Friction can degrade the effectiveness of this method by placing a lower limit on the compliance of a given joint. This friction would be a major problem in this design due to the high gear ratio motors chosen and the small torque's involved in positioning.

After this analysis was complete it was learned that the motor gear heads would produce too much friction for this method to be effective [11].

Sensor Feedback

Endpoint force sensor feedback uses a sensor to measure the force applied to the endpoint of the mechanism. This force information is then used to adjust the attitude of the instrument. Feedback can also be in terms of instrument position. The use of a sensor to determine positioning error bypasses the inner workings of the robot mechanism. This eliminates problems with friction within the mechanism and therefore produces very accurate positioning.

Feedback for such a system could take the form of optical distance sensors. These sensors would be placed on the rear of the vehicle, to help provide rough positioning, or on the instrument itself, for more exact deployment. Optical sensors, such as laser range finders, have many advantages in an application such as this. Such sensors have no moving parts and are vary reliable, also, there is no need for mechanical contact between the instrument and target to determine distance. This also is an aid to reliability since there is nothing to get caught or stuck. Distance could also be measured using sensors such as lvdts (linear variable differential transformer). These sensors have a moving part that contacts the surface and provides distance information.

Yet another method of sensor feedback would involve the use of bumpers . A bumper or bump switch would be used to determine if contact has been made between the instrument and target. This does not present a lot of information in the form of positioning error (i.e. contact or no contact), but, because of the slow motion of the system, may be adequate.

Advantages and Disadvantages of Endpoint Sensor Feedback

Sensor feedback would eliminate problems with friction associated with the joints by only looking at the actual force applied at the endpoint or the actual position of the endpoint. This system would produce terrific positioning of the instrument. However, implementation of this solution would be quite complicated. The force feedback and flexibility of the mechanism can also threaten the stability of the system.

Reliability and stability are a must for any deployment mechanism in this application. Also, 20° angular error is acceptable in the positioning of the instrument so the precision of sensor feedback is not worth it's cost in complexity. For these reasons no form of endpoint feedback is utilized in the current design.

However, additional sensors will probably be added to the rear of the vehicle to augment initial rough positioning of the rover. Also, a rear looking camera will probably be utilized to ensure final positioning of the instrument.

Passive Compliance

Another method of producing this desired compliance is through passive compliance. Passive compliance involves flexibility within the physical make up of the mechanism. This could be in the form of springs, elastic members, or added joints.

A variation on the Remote Compliance Center (RCC) Hand was considered to aid in the positioning of the spectrometer. The RCC Hand is a device that is used to add compliance to the endpoint of a robotic system [18]. This system uses additional links and joints to control the position of the endpoint compliance center. In this application, the spectrometer would be mounted on two links. The axis of these links would intersect at the desired location of the compliance center (as determined in figure 5.3). This point of intersection becomes the instant center of rotation of the spectrometer. This insures that the spectrometer will rotate about the compliance center as it contacts the surface of the target and align with this surface.

This concept is illustrated in figure 5.4. The physical set up is seen on the left and the mechanism in operation is seen on the right. As the spectrometer first contacts the target surface on the lower right hand corner, a reaction force is produced (as in figure 5.3). This reaction force then produces a rotation about the compliance center and aligns the spectrometer with the target surface.

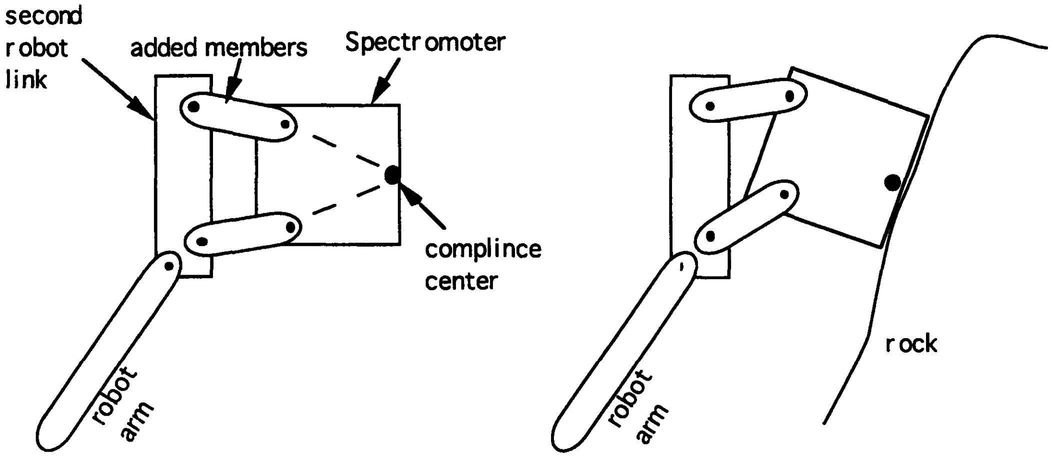


Figure 5.4: Remote Center Compliance Mechanism

A wooden model of this mechanism was constructed to demonstrate the concept. This same concept of passive compliance could be used in the yaw rotation of the spectrometer (rotation about the y-axis in the kinematic analysis) to insure alignment in this direction.

Advantages and Disadvantages of Passive Compliance

Passive compliance has many advantages, the main advantage is that it is very simple and easy to implement. In contrast to other methods of compliance, passive compliance requires no lengthy software or intense computations in its response. Therefore response is very quick, while it does not threaten the system stability. Compliance in this form only provides flexibility over a given operating range, so a roughly accurate initial position is needed. Also, passive compliance can not be easily be adjusted, because the compliance is built in to the mechanism it is difficult to change the level of compliance after fabrication.

A problem with a design such as the RCC hand lies in the complexity of the mechanism. The mechanism has a lot of moving parts, hence a lot of joints. This degrades the reliability of the overall design.

Compliance System Analysis

The various methods of target compliance considered each have their attributes and draw backs, right now the hope is that passive compliance can provide the required positioning accuracy. Passive compliance is simple and reliable, but is limited in performance. Active servo compliance can provide better performance, but in this application joint friction will heavily limit accuracy. Endpoint sensor feedback is very complicated but will provide terrific positioning accuracy, probably more accuracy then is truly required. In an effort to maintain system simplicity, the design was formulated with passive compliance in mind. It is hoped to asses the positioning accuracy of the deployment mechanism on its, then make a decision on the type of compliance needed. A passive compliance mechanism is currently being constructed to be attached to the mechanism endpoint. With this built, the effectiveness of the positioning system can be evaluated. If this performance is not sufficient, a more complicated sensor feedback system will be looked into.

A hybrid positioning system could be employed utilizing passive compliance as well as limited endpoint sensors. A mechanical bump switch could be placed at the top and bottom of the spectrometer contact surface. Then the spectrometer is moved closer to the target until the both the switches have been tripped, this will insure alignment. The effectiveness of such a system would have to be evaluated.

5.6 MECHANISM COMPONENTS AND CONSTRUCTION

5.6.1 Motor Actuators

Two motors were required in this design. Each motor was utilized to actuate one of the degrees of freedom of the mechanism. Motors form Micro-Mo Company were used. This is the same company that produces the motors used as drive motors for the first three MITy prototypes. These motors have proved rugged and reliable.

The motor that drives the first revolute joint is a model 1319. The motor itself produces an output stall torque of .490 [oz-in]. The motor is equipped with a built in gear ratio with a speed reduction of 246:1. This gives an ideal torque output of 120 [oz-in]. The efficiency of the motor's gear head is approximated at 60%, so the estimated output of the motor gear head system is 76 [oz-in].

On the second revolute joint a model 1524 motor is used. The output torque of this motor is estimated at .310 [oz-in]. This motor is equipped with a 76:1 gear head. The estimated efficiency of this gear head is 66% giving an estimated output torque of 15.18 [oz-in].

These motors are also equipped with output shafts of 3[mm]. This complicated gear selection somewhat, such small metric gears are less common then standard gearing.

5.6.2 Gear Selection

Additional gearing was used to transfer the torque from the motor to the axis of rotation of the mechanism joints. A worm gear with a 30:1 gear ratio and a spur gear pair with a 3:1 gear ratio was utilized on the lower joint. On the upper joint a single spur gear pair with a 3:1 gear ratio was chosen.

Because of the sample time required for the spectrometer (one to eleven hours), the lower joint must maintain the same position over extended periods of time, it was hoped this could be accomplished without providing holding power from the motor. For this reason a worm gear was utilized on the lower joint. Since the friction between the worm gear and worm wheel is large, it is not possible to rotate the arm joint without rotating the motor shaft. This prevents the weight of the spectrometer from rotating the motor shaft while the motor is not running. Also, spur gears were used to compensate for any misalignment between the motor shaft and the worm gear shaft. These spur gears were used instead of a flexible coupler because they fit in a very compact space and at the same time increased the motor torque output.

On the upper shaft, a pair of spur gears was also used. These spur gears transferred the torque output from the motor to the shaft that rotates the spectrometer. This made it possible to place the motor above the spectrometer. By placing the motor in this position space on the rover required to house the deployment mechanism was reduced. Also, the use of these gears increased the torque output of the motor.

An inherent drawback to the use of gears is friction. Generally the higher the gear ratio the lower the efficiency of power transfer through the gear train. Worm gears are particularly inefficient when large torque is being transmited. The torque involved to deploy this instrument is not large so the efficiency losses are not as prevelent. Also the time of operation of the mechanism with respect to the overall mission is small. Another factor of the use of gearing is the tradeoff between torque and speed. The large gear ratios used increased the torque output of the motors but decreased the speed. Since the speed of deployment is not terribly significant this was not a problem, and the large torque output allowed the motor size to be reduced.

5.6.3 Bearing Selection

Since this deployment mechanism is a development prototype, the bearings used were not terribly critical. The speed of rotation of the joints will never reach more than a few rotations per minute and will be operated for a very low number of cycles. Also, because of the size of the instrument the loads on the joints will be quite small.

In a space environment bearing selection would be a much larger issue. The extreme temperature variations and fine dust particles found on the surface of the moon or mars, make it a harsh environment for bearings. In this situation, much more attention would need to be given to the bearings, and expensive space qualified bearings would be needed.

5.6.4 Final Prototype Design and Construction

The final design of the deployment mechanism can be seen in figure 5.5. This is the view that would be seen if looking at the rover and deployment mechanism from the rear. Not shown in this view is the lower joint motor and gearing. The mechanism is shown with the lower joint rotated approximately 45 degrees. This allows the upper joint to be seen from this view. This is not the stowed or fully deployed position.

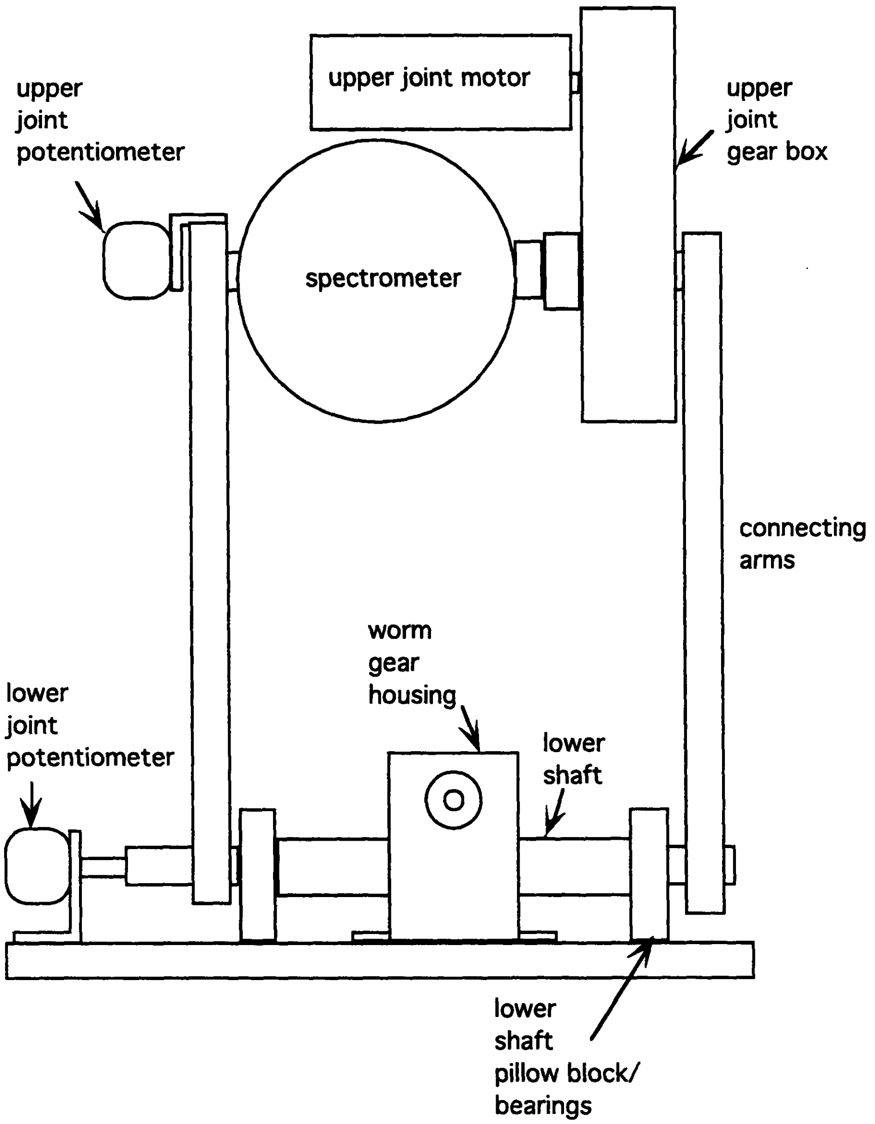


Figure 5.5: Rear View of Deployment Mechanism/Spectrometer

Figure 5.6 shows the deployment mechanism from a side view. The lower potentiometer and one connecting arm are removed in this view to allow the lower joint motor to be seen. Once again the lower joint has been rotated approximately 45° to allow more of the mechanism to be shown.

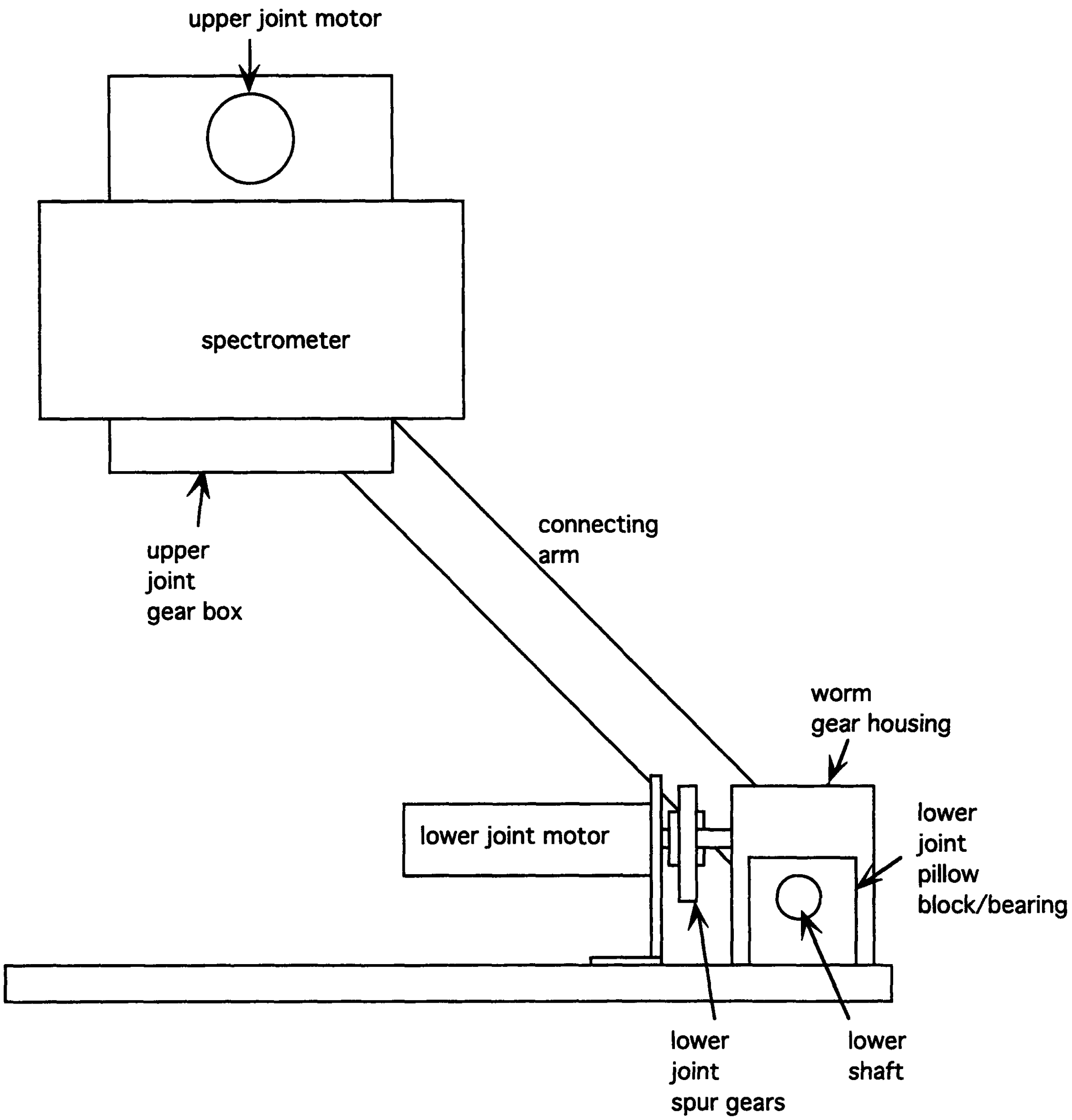


Figure 5.6: Side View of Deployment Mechanism/Spectrometer

It is important to note that the upper joint motor rotates with the spectrometer. This means that this motor will always be directly above the spectrometer. This is done to reduce the area needed on board the rover to house the deployment mechanism. Also, the lower motor and gearing fit in-between the connecting arms, this also reduces the space required to house the mechanism.

The prototype deployment mechanism was constructed over the fall semester and finished at the end of January 1994. The material used was Aluminum 6061 T6, because of its low cost and good machinibility. The finished prototype can be seen in figure 5.7.

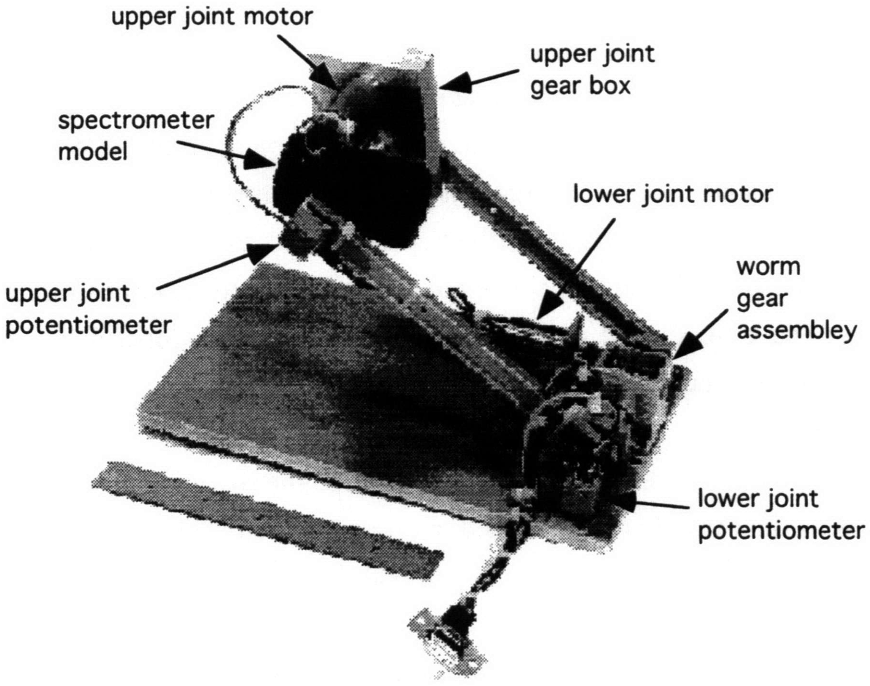


Figure 5.7: Deployment Mechanism Prototype

5.6.5 Integration with Rover Platform

The mechanism prototype was planned for implementation on the third micro rover. The deployment mechanism is powered and controlled by the MITy-3 platform. Physical integration will occur after the deployment mechanism and rover have been tested individually. Packaging of the mechanism and instrument on the rover platform will be critical since space on the rover is premium.

5.7 CONTROLLER DESIGN

The challenging portion of positioning the spectrometer is to integrate the motion of both the rover and deployment mechanism to achieve good spectrometer positioning. A great challenge for the rover will be to identify the target and position itself so that the deployment mechanism can reach the target.

Once the rover has reached its target destination, the area to be examined by the spectrometer, it will begin to identify the final destination of the spectrometer. The rover will use the laser range finder to build a detailed map of the surroundings. From this map the rover will have to identify the destination of the spectrometer, whether it is an open area to sample the ground surface, or it is a large rock to be studied. This will be a challenging job for the rover to accomplish on its own given its sensor limitations. The ground staff will have to aid the rover by making the target a fairly obvious one. Either a large open area or a large rock standing in an open area. Another idea is to pause and return another video image at this stage so that the target can be better identified by the ground support staff. With the target identified, the rover will have to determine a path to the target while positioning itself with the deployment mechanism toward the target. Additional sensors will most likely be needed to aid the rover in positioning. These sensors will have to help the rover determine when it is the proper distance from the rock and if it is perpendicular to the rock. Then the rover can begin to deploy the spectrometer.

Currently, the control algorithm to position the rover is being developed in the three dimensional simulation discussed in chapter three of this thesis. This work is in its early stages and will continue. This is an ideal application for the three dimensional simulation since additional sensors can be modeled and tested before committing to hardware. The effectiveness of this positioning algorithm will be assessed in simulation before implementation on the actual rover.

5.7.1 Controller Development

Because of the very slow speed involved in deploying the spectrometer the dynamics of physical structure are not significant. However the motor response is quite slow, and this had to be taken into account in the controller design.

To position the deployment mechanism a PID control system was implemented. The mechanism has been shown to have more than enough torque to position the spectrometer accurately. During the development of the control system difficulty was encountered with electrical noise in the potentiometer readings. This noise made accurate positioning difficult and made derivative control impossible. Once this electrical problem was solved control system development could continue.

Currently the rover receives position commands from the Zilog microprocessor. These commands are input to the processor through the keypad interface.

5.7.2 Controller Performance and Testing

The time response of the deployment mechanism is not quick. The mechanism takes between 15 and 20 seconds to move from a stowed position to a fully deployed position. This deployment time is more than adequate since deployment speed is not terribly important.

Friction is a major factor in the mechanism joints which can limit positioning accuracy. The elimination of this frictional disturbance is done by the use of integral control. The positioning error of the spectrometer joints during initial testing was consistently less than 3°. The size of this steady state error has been limited by electrical noise in the potentiometer readings. Work is underway to further reduce this electrical noise.

Because of time constraints and delays in the construction of MITy-3, no onboard testing of the robotic deployment mechanism was completed. This will be conducted when MITy-3 has been outfitted with its sensor package. This will make positioning of all components, the deployment mechanism, spectrometer and rover, possible.

5.8 CONCLUSIONS AND RECOMMENDATIONS

Initial testing shows the design to be more than adequate. The accurate positioning of the mechanism joints will make accurate positioning of the spectrometer possible.

Now that the mechanism itself has been built and tested work will be put into a compliance mechanism. A passive compliance device similar to the RCC hand is being designed and built. This device will aid in final spectrometer positioning.

Simulation work will continue to develop an algorithm that will allow the rover to identify the spectrometer target and position itself for deployment. Also the simulation is being used to develop a sensor package to aid in the development of the spectrometer.

Once the deployment mechanism has been fully developed it will be integrated with the rover platform. Work will need to be done in the packaging of the mechanism. As rover development continues adequate space will need to be reserved for the deployment mechanism and a means of shielding the mechanism and spectrometer will need to be devised.

CONCLUSIONS AND RECOMMENDATIONS
CHAPTER 6

6.1 ROVER SIMULATION

6.1.1 Simulation Motivation

A three dimensional kinematic simulation of the MITy rover was developed. This simulation was used to evaluate the hazard avoidance algorithms used to guide the rover. The three dimensional aspects of hazard avoidance had not yet been considered and were investigated with this new simulation. The simulation will also be used to evaluate the rover's performance in an environment reconstructed from images returned from the rover. In this way the actual rover can be helped through difficult areas by evaluating the simulated rover's mistakes. This will greatly increase the performance of the actual rover. Finally the simulated rover can be teleoperated as the actual rover. In this way the simulated rover can be used to evaluate different modes of rover teleoperation.

6.1.2 Simulation Structure

The simulated rover and the ground profile are modeled kinematically. No mechanical dynamics are considered in the motion of the simulated rover. The ground profile is defined as a grid system to be compatible with terrain maps reconstructed from stereoscopic photographs returned from the rover. The simulation includes modeling of each of the rover's hazard avoidance and navigation sensors as well as rover steering and motion.

The rover simulation is augmented by animation software that allows the rover and ground profile to be observed as the rover travels. This simulation and animation software allow both qualitative and quantitative evaluation of rover performance in many different situations.

6.1.3 Results and Recommendations for Hazard Avoidance

The simulation was used to recreate problems encountered in previous rover testing. These problems include: the misdirection of the rover's hazard avoidance sensors (laser range finder and proximity sensors), the difficulty of approaching hills and valleys and the problems encountered with cliffs and sharp drop-offs.

To elevate the problems of sensor misdirection the pitch and roll of the rover platforms were considered to intelligently interpret the hazard avoidance sensor readings.

Also, the hazard avoidance routine's parameters were tuned to handle approaching hills, valleys and cliffs.

6.1.4 Future Work

The simulation is currently being used to test new hazard avoidance routines for other mobile robots under development at Draper Labs. Hazard avoidance testing is not the only use for the simulation. The simulation is being integrated with the current rover ground station software to allow the simulated rover to be teleoperated through this ground station. In the near future the simulation will be used to develop the positioning software for the scientific instrument deployment mechanism discussed in chapter 5.

6.2 MITY-3

The MITy-3 micro-rover is the third prototype planetary rover of the MITy series. MITy-3 uses conical shaped wheels to increase vehicle mobility. The uses of conical wheels reduces the space beneath the vehicle where the rover can become high centered and stuck. This high centering difficulty was a problem experienced with previous rover designs. With the implementation of conical wheels came the need for a new steering system.

6.2.1 Steering

Since conical wheels extend over almost the entire width of the rover, limitations are placed on the types of steering systems that can be used. To steer the vehicle the wheel axle must be pivoted about the axle center point. This requires a large steering torque about this point. In this situation the use of steering linkages or large steering actuators is not practical.

To eleviate this problem three different types of steering systems were considered: free pivot steering, tank steering and hybrid steering. In free pivot steering the wheel axle is free to pivot about its center point. To turn the vehicle axle the wheel on the right side of the axle is driven at a different speed than the wheel on the left side of the axle. In this way the rover axle is rotated and the vehicle is turned. Since the wheel axles are free to pivot the mobility of this steering system comes into question. In tank steering the wheel axles are locked in place. To turn the rover the wheels on the right side of the rover are driven at a different speed than the wheels on the left side of the rover. Hybrid steering is very similar to free pivot steering in that the wheels are driven at different speeds to rotate the axle and steer the rover. In hybrid steering a worm gear is used to mechanically hold the wheels in place as the rover turns. This makes the rover more mobile and less susceptible to disturbances.

It was discovered in testing that MITy-3 did not have the required electrical power to tank steer. A summary of the advantages and disadvantages of each type along with the initial mobility results is shown in figure 6.1.

	Efficiency	Mobility	Reliability	Steering
Tank	poor	---	good	poor
Free Pivot	good	fair	fair	good
Hybrid	good	good	good	good

Figure 6.1: Steering Summary

6.2.2 Mobility

During initial testing MITy-3 did not become high centered at anytime. Testing to this point has not been exhaustive but initial results are better than expected. With the use of hybrid steering conical wheels have eliminated the high centering problem and efficient vehicle steering is still possible. Mobility was slightly reduced when free pivot steering was used.

Testing has shown that the spring steel rods connecting the vehicle platforms is too stiff for the current weight of the rover. This causes the middle rover wheels to be lifted off the ground when the front wheels strike a large obstacle. Another mobility problem is the wheight of the current conical wheels. These wheels exceed the mass allocation for wheels on the rover. The rover is currently capable of climbing a 5" step and it is believed that this can be increased with more flexible connecting rods and lighter wheels.

6.2.3 Future Work

Now that the principles of hybrid steering have been developed it is believed that this type of steering can be improved. The torque required for the worm gear motor during hybrid steering can be quantified and the motor can be properly sized. Also, the diameter of the worm gear can be reduced to shrink the volume of this steering mechanism. Hybrid steering has been shown to be a very effective way to steer a rover with conical wheels.

Also the connecting rods of the MITy-3 rover will be replaced with more flexible rods and testing of this rover's mobility and steering systems will continue.

6.3 DEPLOYMENT MECHANISM

A major task of a planetary rover will be to transport scientific instruments to various locations. The development of a mechanism to deploy such an instrument is discussed in chapter 5. The design focuses on the Alpha-Proton X-ray Spectrometer (APXS) instrument developed for planetary rovers.

The deployment mechanism has to move the instrument from a stowed position on the rover to the operating position for this instrument. The mechanism will have to hold this instrument against a rock or against the ground for an extended period of time (1-11 hours). To accomplish this a two degree of freedom mechanism was developed.

The accurate positioning of this instrument in an unknown environment is a challenging aspect of this design. Different types of endpoint compliance were considered to eleviate this difficulty. Active servo compliance, endpoint sensor feedback and passive endpoint compliance were all considered. Passive compliance was chosen because of its simplicity.

6.3.1 Performance Evaluation

The deployment mechanism has been built and a control scheme has been developed. Initial off-board testing has been conducted and has been very successful. The structure is more than adequate and a joint positioning accuracy of 3° has been achieved. This accuracy has been limited by electrical noise in the sensor feedback. Work is underway to reduce this problem.

6.3.2 Future Work

The design and construction of a passive compliance mechanism is currently underway. This mechanism will be used to improve accuracy of final spectrometer positioning.

Integration of the deployment mechanism with rover platform will be the next step in deployment mechanism development. Positioning of the rover along with the deployment mechanism to achieve accurate spectrometer positing will be vary challenging.

The procedure for the fully developed system will be for a ground crew to choose a target form a video image returned by the rover. Then the rover will need to travel to this target and position the spectrometer autonomously. In order to accomplish this, work will need to be done in the rover's ability to identify the target and the rover's ability to position itself so the target can be reached by the deployment mechanism.

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