The Mars Ball Project

Technical Report

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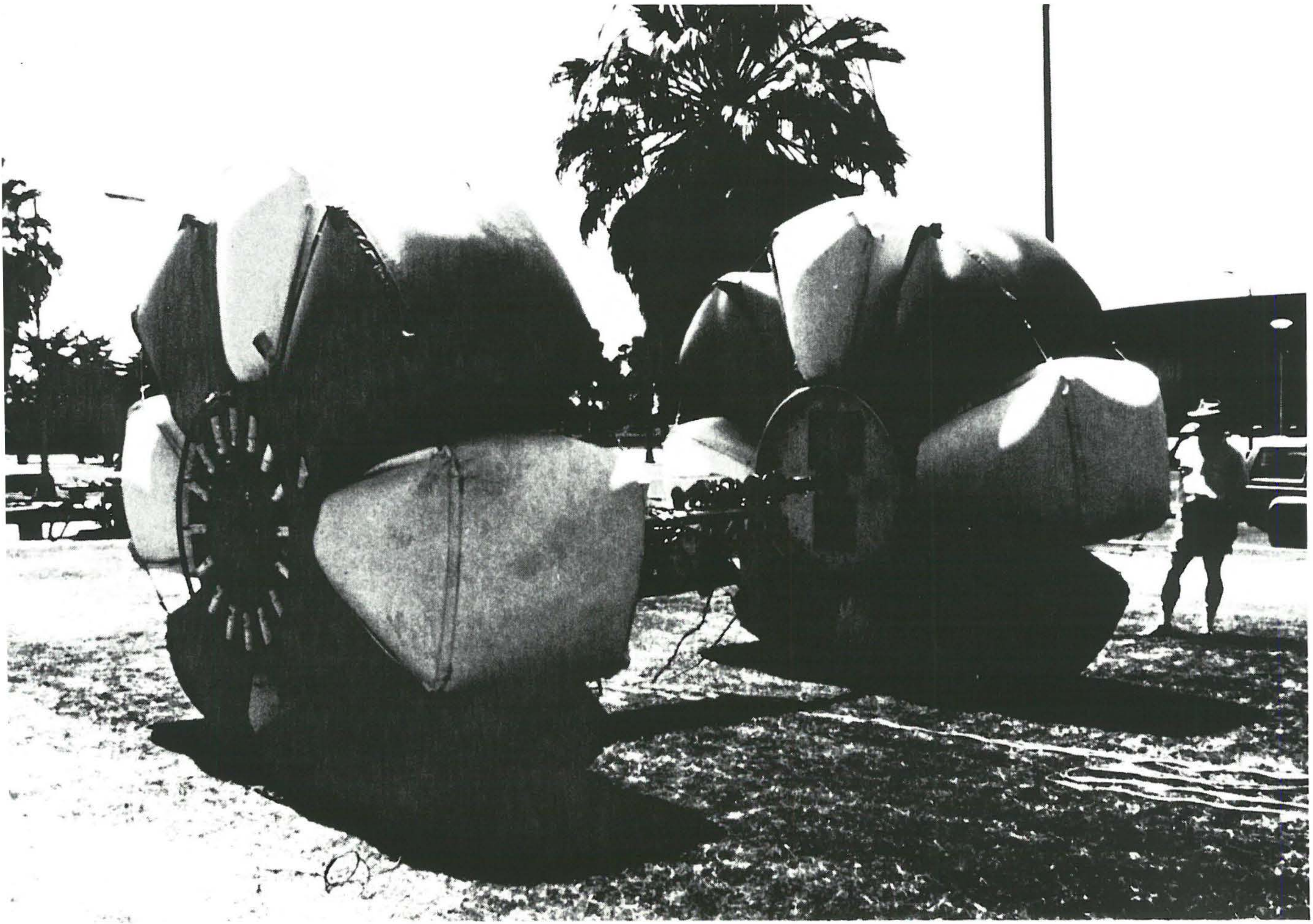

Table of Contents

Acknowledgments

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1. INTRODUCTION

1.1 Purpose

The next logical step in the exploration of Mars is an unmanned mission in which a roving vehicle plays an important part in the scientific investigation. The purpose of sending a rover to Mars is really two-fold. We seek to examine as much of the planet's surface in as detailed a manner as possible in preparation for the safe landing and return of future human explorers. In addition we are trying to answer profound and significant questions about the origin and present conditions of the Solar System, particularly the terrestrial planets.

Previous missions to both the moon and Mars have demonstrated the limits of what can be determined regarding surface properties from orbiting spacecraft. The landing site for Apollo 11, arguably the most carefully chosen site of all time, proved to be littered with boulders which could have caused a catastophic end to the mission had there not been the on-board capability for direct control of the landing. The Apollo 16 site was chosen on the basis of photos returned by earlier Apollo flights which showed that it consisted of "fresh lava flows". In fact it turned out to be dust and ejecta from nearby craters. While this did not affect the safety of the landing, it certainly altered the nature of the science which was carried out. The Viking spacecraft were set down in the smoothest areas of Mars which could be found from orbit. These landing sites proved to be rock-strewn and hazardous to safe landings. These experiences have demonstrated that there is no substitute for actually landing and moving around on the surface to determine even the most basic properties of that surface.

A mission to Mars with an accompanying rover would be able to address the question of how Mars formed far more extensively than a comparable mission which is limited to testing only its immediate surroundings. It should elucidate Mars' present condition, and help answer the fundamental puzzle of planetary science: how did the Solar System, and with it, the Earth, form? Some of these questions concern the presence or absence of certain substances on Mars, substances which a rover could measure *in situ*. As one example, a determination of the amount of water that presently exists on Mars would not only help shed light on the origin of Martian surface morphology, but would also indicate the degree to which Mars has retained volatile elements since its formation. Accurately gauging the total amount of water on Mars is a task much more appropriate to a rover than a single site mission.

1.2 General Martian Geology

In order to achieve these objectives, we must consider the general Martian geologic and topographic environment. The Martian landscape and topography can be generally described by dividing the surface into several distinct regions, each exhibiting a unique feature.

Fifty percent of the planet, including most of the southern hemisphere, is heavily cratered ancient terrain, a product of the early heavy bombardment. To the north are the Tharsis bulge and the northern plains. Here lie volcanic mountains and slopes as well as very old small volcanic constructs. Dark banded layers along canyon walls have been interpreted as basaltic stratigraphy, which would imply episodes of ancient volcanic activity.

Mars has polar ice caps which cover two to five percent of the planet. The southern ice cap is seasonal and composed almost entirely of frozen carbon dioxide, while the northern pole has, in addition to the dry ice component, a permanent cap of residual water ice. Evidence for sedimentary rocks lies in the presence of layered deposits around the poles. There is also some indication of thick layered ash flows or aeolian deposits around Amazonis Planicium.

Deep canyons and many valleys cut across the planet. Valleys and channels constitute less than 10% of the surface but provide a great deal of the impetus for the search for water. These channels demonstrate signs of catastrophic flooding, gentler erosive processes within streambeds and water storage beneath ground as permafrost.

1.3 Surface Properties

Any rover sent to Mars should be capable of traversing as many of these diverse terrains as possible. Photographs returned by the Viking 1 and Viking 2 missions from two separate landing sites show fragments of rock from a few centimeters to a meter in dimension (see Figures 1.1 and 1.2).

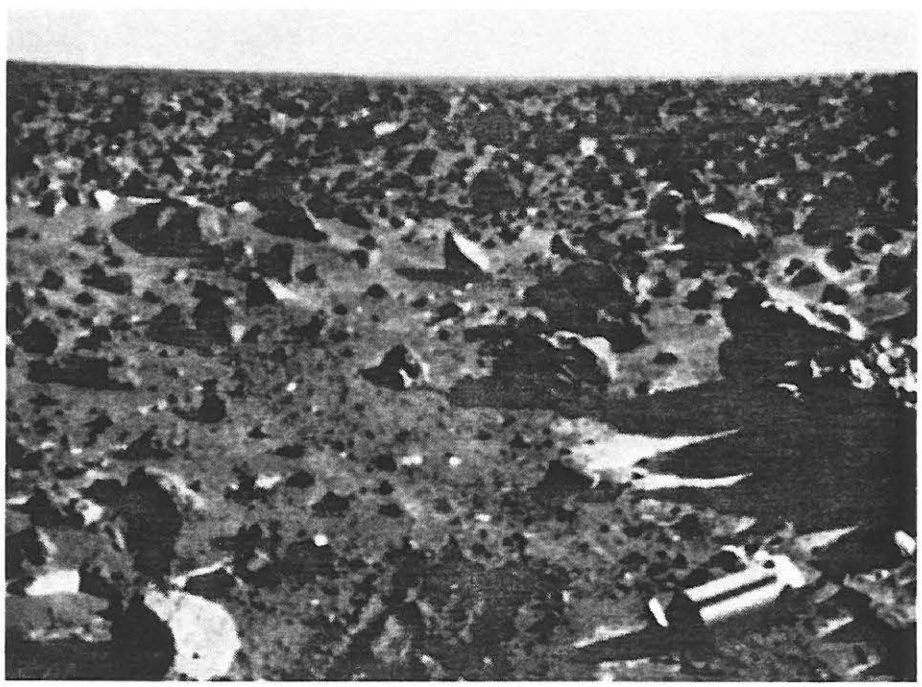

Figure 1.1. Viking 1 Lander site, Chryse Planitia. NASA Pic. No. 22A252/030.

Figure 1.3 shows that the size distribution of rocks at the two sites are re-

Figure 1.2. Viking 2 Lander site, Utopia Planitia. NASA Pic. No. 22I109/1050.

markably similar. The mean rock diameter at the Viking 1 site is 51 mm, and at the Viking 2 site it is 61 mm. The largest rock observed in the near field is "Big Joe" of the Viking 1 site, with a diameter of 2 meters. Rocks with diameters larger than 0.3 m occur approximately every 3 meters. The Viking 1 site, Chryse Planitia, has been described as a weathered volcanic plain [1]. Viking 2, in Utopia Planitia, appears to have landed in a rock field dominated by blocks of crater ejecta. The fact that the rock distributions of two sites with such different geological histories are essentially identical lends some confidence to extrapolations to other Martian terrains. Attempts to apply radar or thermal inertia data towards such extrapolation have been inconclusive, however.

Slopes at the Viking 1 site are quite gentle, averaging 1.5°. Large scale sand dunes of fine grained material are visible. The most prominent features seen are ridges with heights of approximately 5 meters. The Viking 2 site is remarkably flat.

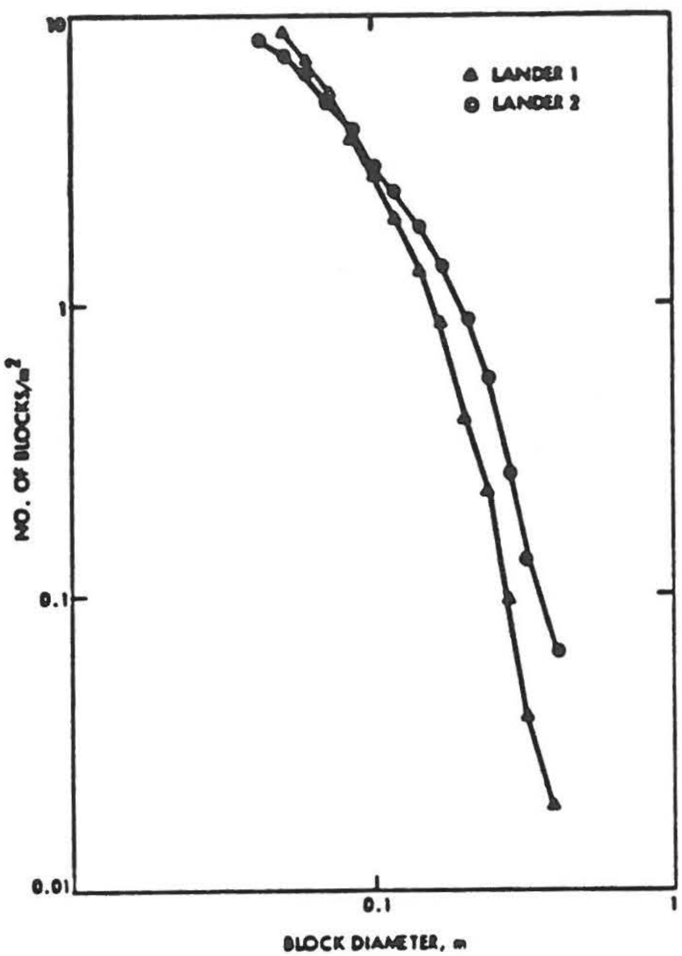

Figure 1.3. Cumulative size frequency distribution of rocks near Viking Landers 1 and 2 (from Garvin et al. [14]).

Stereoscopic mapping shows that all relief to a radial distance of 100 m is less than 1 m. The maximum slopes seen along the horizon are 1 to 2 degrees [2].

It is important to remember, however, that the two Viking landing sites are the only portions of the Martian surface which have been explored in detail. Since they were chosen for their flatness and lack of features, these sites are located far from the most interesting geological areas.

1.4 Required Capabilities

Any Martian rover should have enough mobility to visit several qualitatively different types of terrain during the mission, given the challenges that the Martian landscape and environment offer such an automated probe. The rover must be stored during launch and transport and landed safely. It must carry enough power to move, perform its tasks, and communicate with Earth in this hostile setting, all the while being prepared for the unexpected and unforseen: situations for which Earth-based engineers were not able to plan.

To this end, NASA has listed a set of tentative criteria for Martian rover designs [3]. These require that the total vehicle weight be less than 700 kg including 100 kg of scientific instruments. The vehicle must provide for the storage and transportation of 1.3 m^3 of material. It must be capable of covering 1 km/day over a total distance of at least 80 km and negotiating slopes of 30° over smooth terrain and 20° on loose sand. Navigational accuracy requirements were also listed but are not intrinsic to a given rover design; they represent a separate issue, which is not addressed here.

In addition to these mobility requirements, the rover should be able to carry and deploy scientific instruments in a useful manner. Such instruments include: dust and rock analysis systems, gauges to measure fundamental environmental parameters like atmospheric pressure, spectrometers and imaging equipment, means for *in situ* chemical analysis, seismometers, and sampling drills. All aspects of the planet accessible to the rover such as sub-surface, surface and atmosphere, should be sampled, measured, and studied by as many experiments as can be effectively placed on the vehicle.

1.5 Past Rover Designs

The design of wheeled rovers for lunar and planetary missions has been a topic of some interest since the mid-1950's. During the 1960's and 70's, when the focus of space programs was centered on the moon, both Soviet and American designs for wheeled rovers emerged. Two Lunokhods completed very successful rover missions in the early 1970's [4]. These eight-wheeled rovers ran on solar-powered storage batteries, traversing over 10 km of terrain on missions lasting up to 11 months. The Lunokhods were directed by means of a real-time interactive system wherein images of the lunar terrain ahead of the vehicle were sent to Earth and directions for further motion returned to the rover. Despite the Lunokhod successes, the quintessential lunar rover was the lunar roving vehicle carried on the Apollo 15, 16, and 17 missions [5]. This 209 kg vehicle carried twice its weight in payload (rocks and astronauts) at speeds of about 10 km per hour. Powered by storage batteries, the Lunar Rover had a range of 92 km, and could tackle 0.3 meter step obstacles, 0.7 meter crevasses, and slopes of 25°. Of course its overwhelming advantage was its sophisticated onboard guidance computer, i.e. an Apollo astronaut, who also acted as sampling arm, hazard detector, course selector, and emergency mechanic.

With the Viking program underway in the mid-70's, rover designs competed to take advantage of Mars exploration missions expected to follow later in the decade. A mini-rover deployed from a Viking lander was discussed by JPL in 1978 [6]. This vehicle, tethered to the lander for power and guidance, would weigh 30 kg and carry an 8 kg science package, including a sampling arm and TV camera [7]. With a range of 200 m, the mini-rover could operate for months, traveling 10 m per day on its two wheels. The limited capabilities of the mini-rover contrasted sharply with a 'full capability' rover, weighing 400-500 kg and carrying 80-100 kg of scientific payload [6]. Designed to soft-land directly on the Martian surface, this rover could travel hundreds of km during a traverse lasting one Martian year, covering perhaps 400 m per day. Both a six-wheeled and a four-legged, tracked version of this scale have been proposed, with the tracked configuration thought better able to deal with obstacles.

Other non-wheeled alternatives appeared in the 1970's to compete with conventional designs. The Mars Hopper could travel hundreds of km across Mars by blasting off on a ballistic trajectory to land at another area of interest [8]. The Mars Airplane concept would deploy a light propeller-driven science platform that would cruise the planet for several days before soft-landing and finishing its mission on the surface. Balloons have been considered as an unguided instrument transport mechanism. There is also continuing university and defense-related work on multi-legged vehicles for Earth-bound use; these negotiate rugged terrain with an insect-like gait. Perhaps this mode of travel would prove well-suited to Martian obstacles, but the vehicles are mechanically and computationally complex. Probably stranger than any of these rover designs, though, was the original concept for the Mars Ball, circa 1978.

1.6 The Mars Ball

As envisioned by Jacques Blamont and his co-workers at CNES, the Mars Ball (Figure 1.4) was an inflated sphere of 6.5 meters diameter, weighing 175 kg and carrying a 35 kg payload internally [9]. By pumping fluid internally it could alter its center of gravity enough to move at 2 m/s on flat terrain in calm winds. In the presence of sufficient wind, it could roll at 80% of wind velocity without fear of damage to its flexible exterior. Inflatable chambers positioned just beneath the sphere's surface would propel it up slopes of 10 to 15 degrees. For surface experiments the Ball would partially deflate and cameras and other instruments could be deployed from the interior through portholes.

This design suffered from problems such as stability in high winds, control of waste heat from its radioisotope generators, a tendency to spiral in to the lowest point on the topography, and deployment of instruments through the sphere. Blamont then suggested a two-wheeled design propelled by pneumatics [10]. This vehicle would weigh about 370 kg, with a 95 kg payload. This idea was the immediate

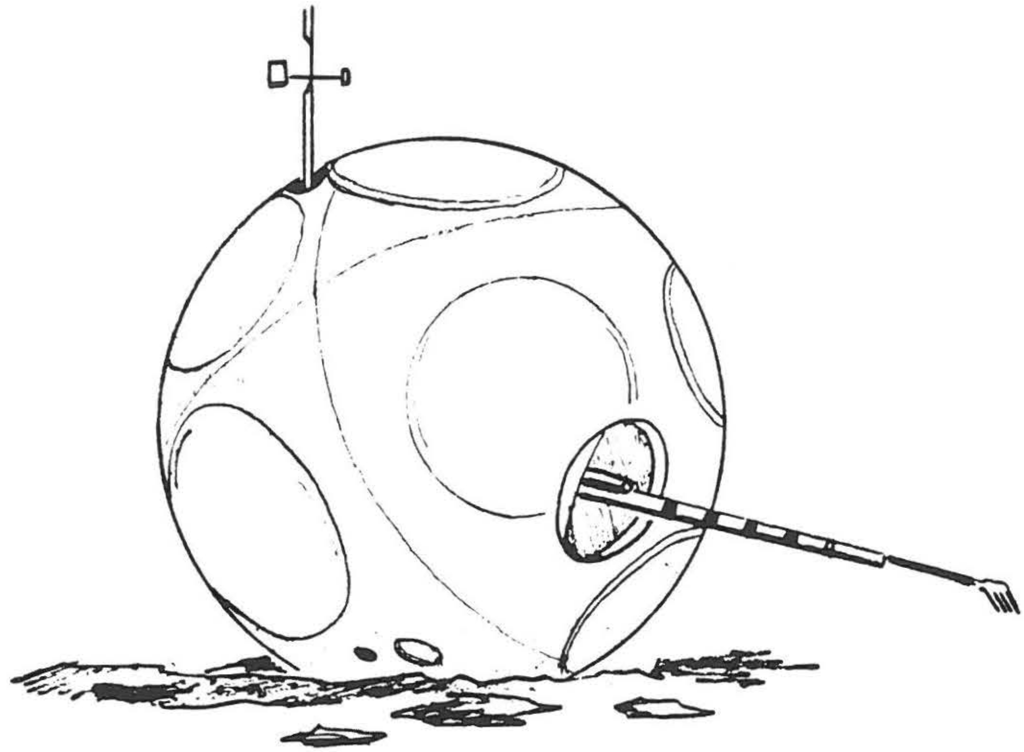

Figure 1.4. Artist's rendering of Blamont's original Mars Ball proposal.

progenitor of the current Mars Ball Project.

Blamont and his colleagues completed an extensive paper study [10] which included construction and propulsion details, thermal analysis, deployment on the Martian surface, and scientific applications. The vehicle they studied (Figure 1.5) was composed of two large inflatable tires, with inflated hemispherical end caps to eliminate the possibility of becoming permanently upended. The inflatable portions of the vehicle were to be laminated composite fabric. The base fabric chosen was Kevlar because of its property of remaining flexible at low temperatures known to occur on Mars. Additional layers were added to provide protection against abrasion and ultraviolet radiation.

Although it is still called the Mars Ball for historical reasons, the current

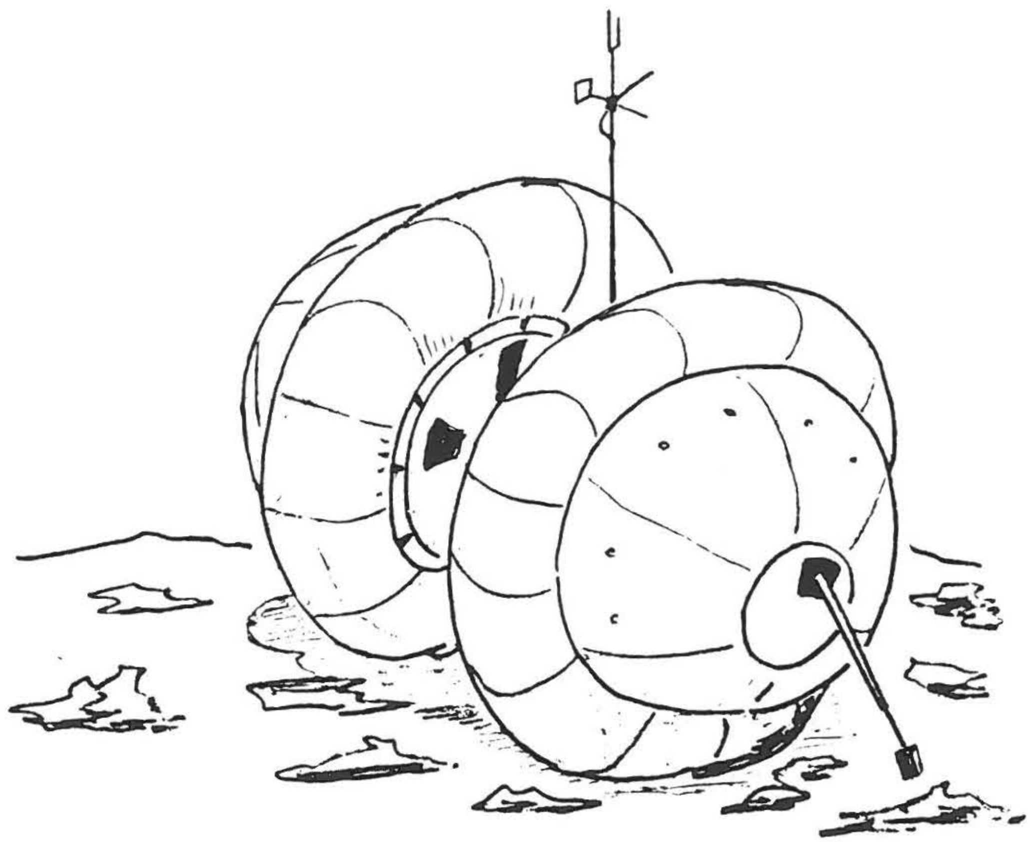

Figure 1.5. Artist's rendering of two-wheeled, inflatable concept for the Mars Ball studied by CNES.

concept calls for two wheels on a single axle which carries the payload. The wheels consist of a hub surrounded by inflatable "sectors" which are inflated and deflated, causing the Ball to roll.

The Mars Ball design had very promising theoretical characteristics, but had never been built and tested in the field. Construction of a working model based upon this premise was necessary to see whether the actual performance of such a novel propulsion system would deviate significantly from the calculated performance. A prototype of the chambered tire design called for no new technology in materials or components, but had never been built. The Mars Ball concept seemed to be relatively simple to design and build, and one which would otherwise be neglected in favor of more traditional designs. A group of graduate students and faculty at the Lunar and Planetary Laboratory (LPL) of the University of Arizona decided that building and testing a prototype Mars Ball could yield several useful results, in particular a determination of whether such a design was feasibile.

The Mars Ball design does not depend on the Viking observations to define the "worst case" specifications, but does use these terrains for a model of the characteristic Martian landscape to be traversed. An advanced knowledge of every potential hazard will never be available to any Martian rover. If this database existed, the rover might not be necessary. That is, the capabilities of an autonomous rover must not be limited by our present or future knowledge of surface properties. It should be fail-safe in the sense that any obstacles it cannot negotiate will be detectable from a safe distance, allowing the rover to stop and radio for instructions. Large tire size increases the average interval between such hazards for a given surface, increasing the amount of time the rover spends in motion, thus allowing longer traverse lengths for a given mission duration. A Mars Ball with fully-inflated tire diameter of 4 meters should be able to tread over obstacles approximately 75 cm in size. For such a vehicle, most observed Martian rocks would no longer be obstacles, allowing autonomous traverse perhaps halfway to the horizon between contact with the Earth. We estimate that this vehicle could travel up to 2 km per day, perhaps allowing traverse lengths of several hundred kilometers over the mission's duration. This capability, and proper landing site selection, would enable the vehicle to survey a variety of terrains of diverse ages and origins.

2. THE MARS BALL PROJECT

2.1 Introduction

In the spring of 1983 Laurel L.Wilkening and Donald M. Hunten, professors at the University of Arizona Lunar and Planetary Laboratory suggested that the graduate students of the Department of Planetary Sciences form a working group to test the concept of the Mars Ball. The goal of the group would be to design and build a rover based on Blamont's concept, and to test it on terrain simulating typical Martian surface. All project members throughout the course of the project have been graduate students, although specific student participation has changed over the years with the changing graduate student population. These students have all been working towards their Ph.D. in the Department of Planetary Science and have volunteered their time for the project. Due to the broad nature of planetary sciences, the students have had varied backgrounds providing different perspectives to the project.

The project is funded by NASA grant NAGW-546. Initial funding was for the sum of $50,000 with an additional grant of $20,000 awarded in the Spring of 1986.

2.2 General Vehicle Design

The major objective of the Mars Ball project is to test the feasibility of a new method of propulsion. The Mars Ball design calls for two large tires connected by a single axle which carries the vehicle payload. Rather than applying torque to a wheel's axle, this vehicle propels itself by altering the shape of its tires. It

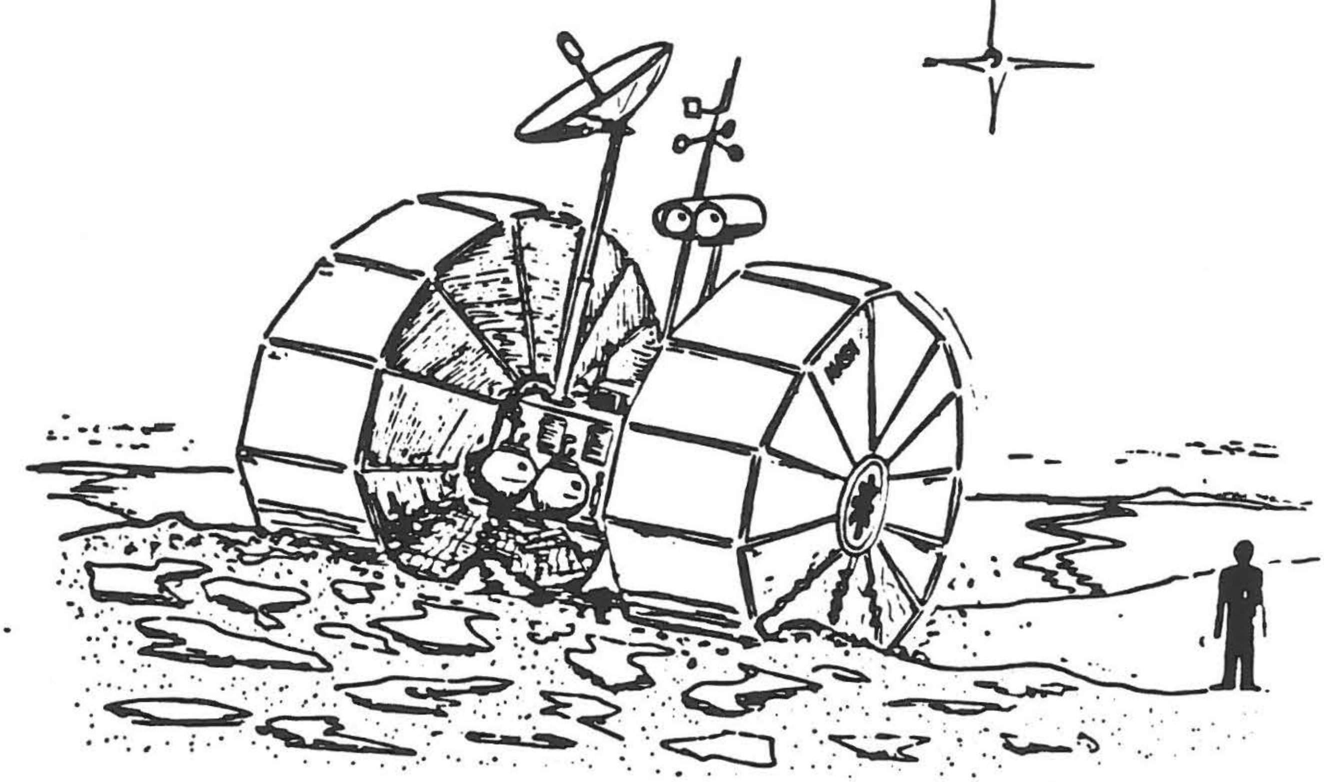

Figure 2.1. Artist's rendering of an actual Mars Ball as envisioned by this study.

accomplishes this by sequentially inflating and deflating tire sections (Figure 2.1).

Each wheel consists of a central cylindrical chamber which contains the mechanisms for compressing the air and an airtight chamber for storing a supply of pressurized air, a series of valves and piping for controlling the flow of the air, and computer circuitry for directing the operations of the individual wheel. Arranged around the circumference of this central cylinder are a series of airbags or sectors which inflate and deflate as air is pumped in or let out. The sectors are mounted to the central cylinder by a flanged seal. The bag is open to the cylinder wall within this seal. For each sector, an airflow tube pierces the central hub to allow air to enter and leave the sector. The airflow tubes contain a system of remotely controlled valves which direct the flow of air either from the central compressed air chamber to the bag or from the bag to the atmosphere.

The vehicle has a single axle from which a freely swinging payload is suspended. Consequently, there is no right-side-up, and the vehicle cannot not be "overturned". The payload consists of a rectangular shaped steel framework which would house scientific instruments, and from which the instruments could be operated. It can also contain computers and control systems which communicate with subsystems located in the hubs via slip ring connectors.

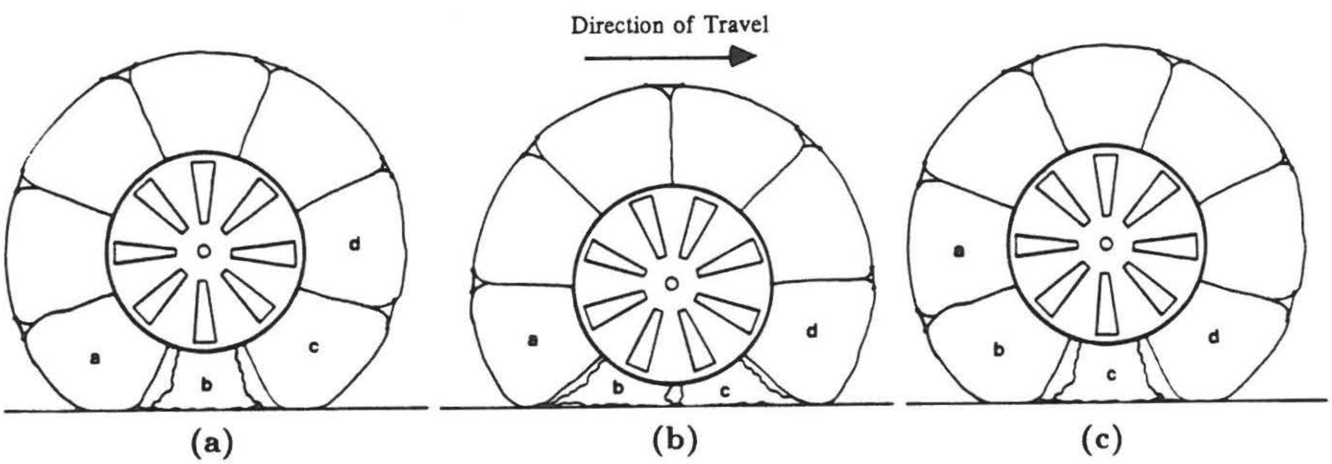

Figure 2.2. Mars Ball rolling sequence. (a) Position of sectors at the start of a forward motion sequence. (b) Position of sectors after deflation of forward sector 'c'. (c) Position of sectors after inflation of sector 'b'. The wheel has now completed one-eigth of a revolution and has returned to its original configuration.

2.3 Motion

The Mars Ball moves by means of co-ordinated inflation and deflation of its sectors. Figure 2.2 shows how the vehicle is propelled by this process. As a starting condition, assume that seven sectors are inflated with one deflated sector directly beneath the vehicle (a). A sector in the direction of desired travel, immediately adjacent to the deflated sector, is deflated by venting to the atmosphere. The vehicle then rolls in this direction, and the weight of the vehicle helps expel the air from this sector (b). The sector which was initially deflated is then filled with air, causing the vehicle to rise and fall forward until it regains its initial configuration (c). The vehicle has thus advanced a full sector, and is now ready for the next set of commands. By changing the number and order of deflated sectors, the rover can roll forward or backward, turn, climb obstacles and ascend slopes.

In order to achieve motion, the Mars Ball requires sectors that are flexible enough to conform to rough topography and yet durable enough to maintain pressure when inflated, even after considerable wear and tear. The pressure required in the tires is a function of vehicle mass, gravity and tire size. If we assume no significant structural support is gained from the sector fabric, then the minimum pressure required is:

$$P = mg/A$$

where A is the area of the tire footprint. For $A = 0.5$ m^2 and $m = 250$ kg, on Earth P is 0.05 atmospheres (50 millibars), easily attainable with centrifugal blowers. On Mars the required pressure would be 15.0 millibars or 2.5 Martian atmospheres; therefore a compressor system would be necessary.

However, there are practical limitations on the degree to which footprint area and internal pressure can be interchanged, conserving force. Sector rigidity also affects the stability and performance of the vehicle, as described in Chapter 5. Pressures higher than these minimum values may therefore be desirable.

The theoretical climbing ability of the Mars Ball has been evaluated by calculating the maximum slope that could be ascended as a function of both the number of sectors in a wheel and of the fraction of the tire's radius which is deflatable. Figure 2.3 shows the idealized geometry of a climbing situation. The tire is on a slope inclined at an angle θ to the horizontal. It is divided into n sectors, each

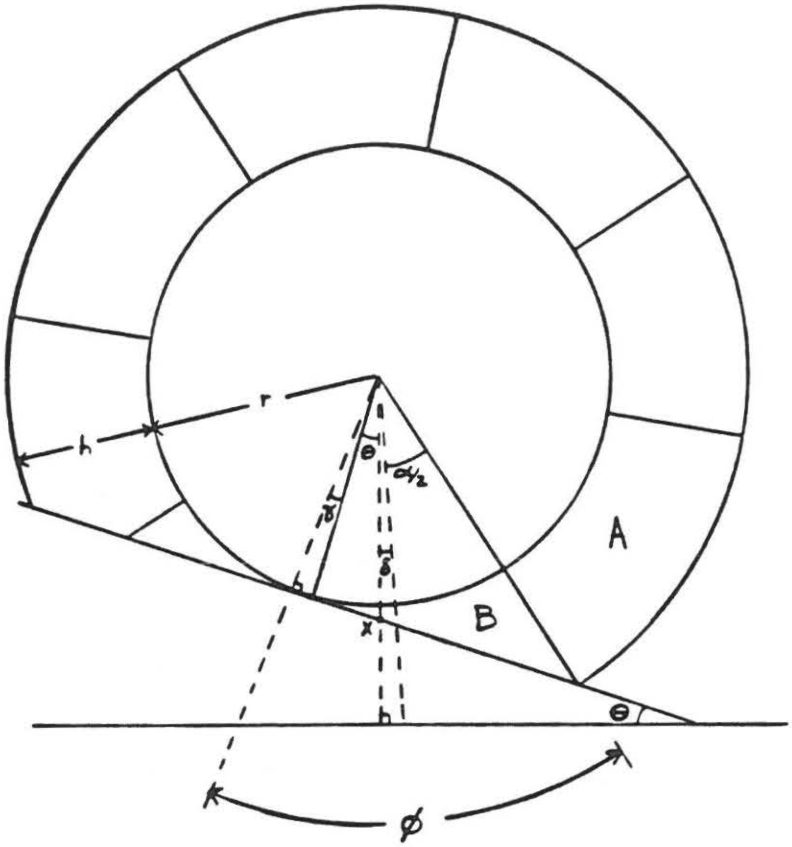

Figure 2.3. Idealized climbing geometry of a Mars Ball wheel. Refer to text for labels and discussion.

of angular extent α. The minimum deflated radius, r, may be determined by a physical division within the tire or it may be an effective value determined by the maximum amount of deflation available. The radial extent of the inflatable portion of the tire is designated h.

Consider the instant when chamber A has just reached maximum inflation and sector B is beginning its push. The criterion chosen to insure that the component of force along the slope is in the uphill direction is that $\delta > 0$. This means that more than half of the footprint area is downhill from the point x, which is directly below the center of mass. Since a real footprint would be considerably narrower at its downhill extreme, δ must be increased accordingly. Geometrically, this requires that:

$$\alpha/2 < \phi - \theta$$

where

$$\phi = \sec^{-1}\{(r+h)/r\}$$

Solving for the radius variables, the result is:

$$h/(r+h) > 1 - \cos\{(\alpha/2) + \theta\}$$

as the necessary condition for a successful ascent.

This relation is shown graphically in Figure 2.4 for tires with 8 and 16 sectors. Actual performance would probably not be as spectacular as these curves indicate due to the neglected complexities of factors such as tire slippage, fabric crumpling, sector misalignment, etc. However these calculations do demonstrate that even an eight-chambered tire with a 30% to 40% inflatable fraction should easily be able to climb the Martian slopes discussed in Chapter 1.

The vehicle surmounts individual obstacles by different processes depending on the size of the obstacle. Generally, objects smaller than a sector will simply be absorbed by the tire as the sector molds its shape to that of the object. Objects larger than a sector are climbed as slopes.

2.4 Advantages of Basic Concept

This two-wheeled, single axle design offers several intrinsic advantages. The main advantage of the wheel design is the large size of the wheels. Their size tends to raise the payload away from surface hazards, so that the vehicle is better able to negotiate rough terrains. The large inflatable segments also serve to smooth out surface obstacles, thereby avoiding the necessity for highly sophisticated on-board

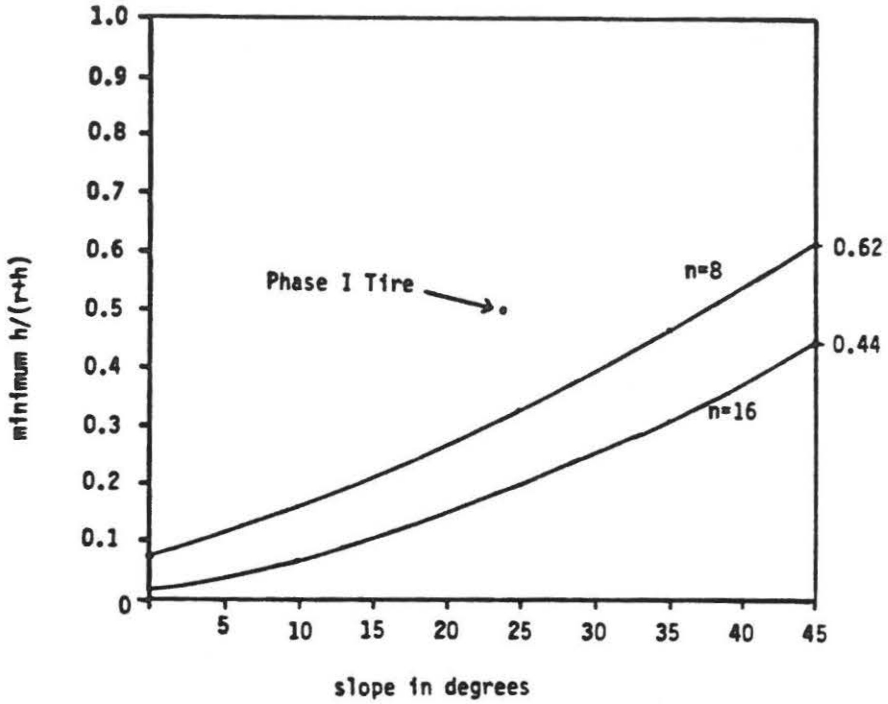

Figure 2.4. Inflatable fraction of the wheel necessary to climb a given slope. Curves are for ideal wheels with 8 and 16 sectors. Actual performance of the Phase I wheel is plotted.

intelligence or constant communications with Earth. Since the vehicle would be launched and transported to Mars with all sectors deflated, these advantages of scale may be gained without requiring a large launch size. Indeed, since the vehicle consists of only two wheels joined by a single axle plus payload unit, it is readily adaptable to the shape of a typical payload launch.

Despite its large size, the Mars Ball is highly maneuverable and stable. Its turning radius is its own width and is smaller than that of a similarly-sized four-wheeled vehicle. While its width greatly reduces the likelihood that the vehicle can be overturned, its lack of any intrinsic up/down or forward/reverse directionality means that even a complete overturn would not prevent the vehicle from continuing its mission. Finally, such a vehicle requires a minimum of new technology.

The Mars Ball design, then, offered enough promising theoretical advantages to prompt project members to design, construct, and test two working prototypes. The prototypes are described in more detail in Chapter 3 (Phase I prototype) and Chapter 4 (Phase II prototype), while test results and a performance review of Phase II are discussed in Chapter 5.

3. PHASE I VEHICLE

3.1 Design and Construction

As the concept underlying the Mars Ball's method of motion had never been explored, we deemed it appropriate to initially build a greatly simplified version of the vehicle. This approach allowed us to determine the basic characteristics of such a vehicle before making major design decisions. Construction of this Phase I vehicle began on a very limited budget. The Ball was fabricated of common materials readily available at local hardware stores.

The design of the Phase I vehicle is detailed in Figure 3.1. The main hub (3.1a) was constructed around a cylinder approximately 19 cm in diameter and 35 cm long. This cylinder was fashioned from a 35 by 76 cm rectangular piece of sheet metal flashing rolled into a cylinder and bolted together at the seam. The cylinder was capped with two plywood end pieces, each 61 cm in diameter and 6.3 mm thick, and centered on the end pieces by means of a smaller shoulder disk of plywood glued to each end piece. These three pieces were then assembled and held in place on a 28 mm diameter wooden axle with collars of 19 mm plywood and locking bolts. The 61 cm diameter of the plywood end pieces provided a flange which extended 18 cm outward from the cylinder.

Air was distributed to sectors located around the cylinder through plumbing (3.1b) fitted through and fastened to the sheet metal cylinder. Independent inflation of the sectors was acheived by means of individual valve assemblies within the tubular fittings connecting each sector and the cylinder. Each unit contained a leather-diaphragm, solenoid-actuated valve of the type used in many church organs.

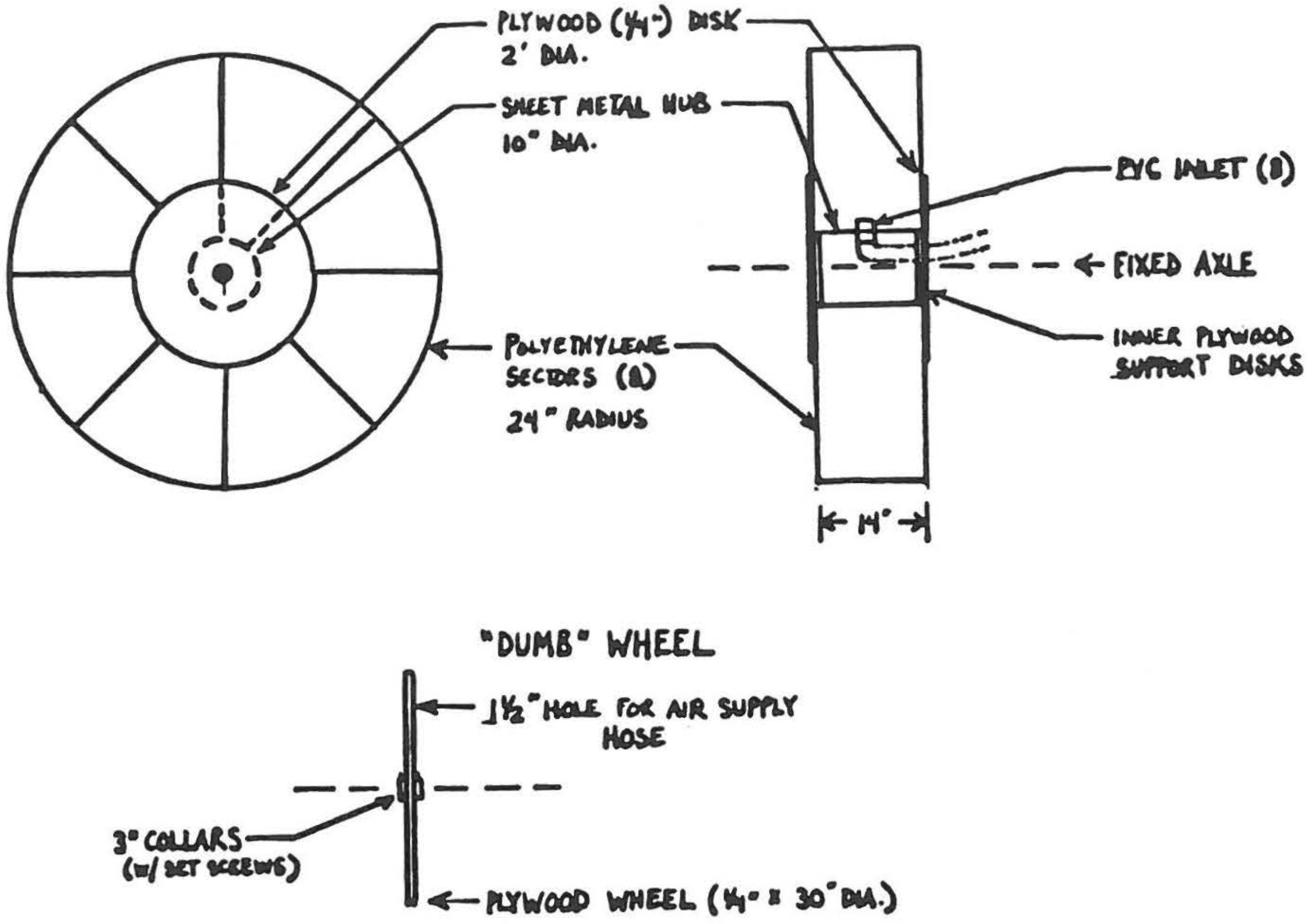

Figure 3.1a. Schematic of Phase I wheel construction. "Dumb" wheel occupies one end of a central axle and supplies support only.

When in the "on" position each valve connected its respective sector to the blower for inflation. In the "off" position, the sector was open to the atmosphere and thus deflated at a rate determined by the amount of vehicle weight on it. Each valve assembly was connected by cable to a bank of 8 manually operated toggle switches and a 12V DC power supply. This off-vehicle arrangement allowed an operator to control inflation remotely.

Sectors were constructed of 0.08 mm thick, 117 liter capacity plastic bags attached to the fittings outside the central cylinder by string wound tightly around

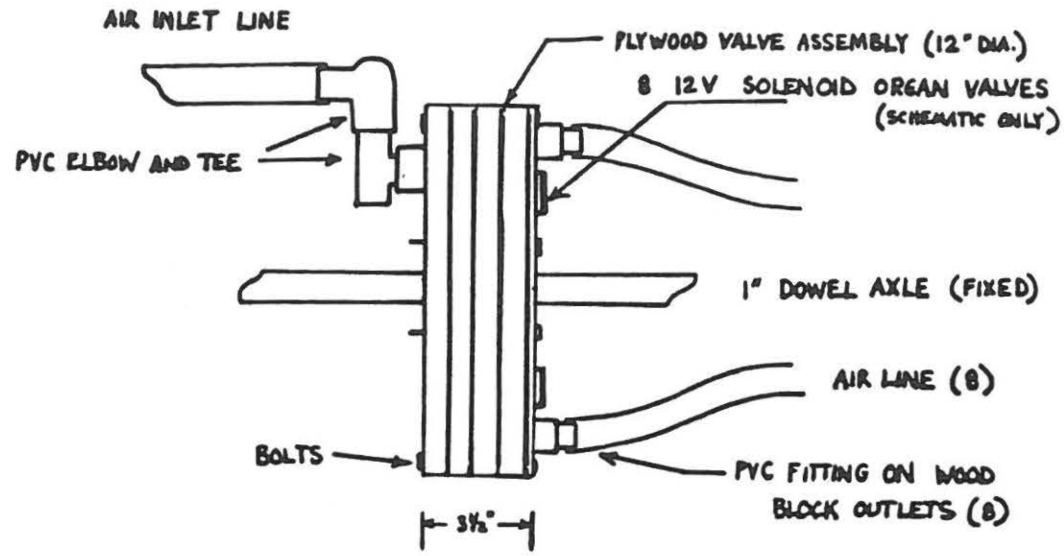

Figure 3.1b. Details of Phase I hub, valves and air supply.

a groove in the fittings. A perfect seal was not necessary at this point due to the large capacity of the blower. These bags were contained within an outer envelope of clear 0.15 mm thick polyethylene. The primary function of the polyethelene envelope was to reduce the strain due to air pressure on the bags. By supplying a set of enclosing walls with a smaller volume than that of each bag, this envelope was able to relieve a large portion of the strain and to reduce the frequency of ruptures. The envelope was constructed of numerous sections of polyethylene which were cut to shape and sewn together with a conventional household sewing machine. Each envelope consisted of two annular sidewalls, eight radial partitions, and an outer circumferential piece. The sidewalls were further subdivided into eight wedge-shaped sections, each with an inner radius of 12 cm and outer radius of 62 cm. This subdivision allowed the attachment of the inner partitions along radial seams at the boundary of each pair of adjacent sidewall sections. The radial partitions were trapezoidal in shape such that the outer edge of the tire was wider than the hub (50 *vs* 36 cm). This feature was included in the design as an attempt to provide additional stability to the tire when in operation. The circumferential piece was a rectangular strip with a width of 50 cm and a length of 3.9 m.

When completed, the envelope was attached to the ends of the sheet metal cylinder described above, using machine screws and fender washers to reduce tearing of the polyethylene. A felt tread was attached to the circumference of the tire in order to increase traction. The tire thus formed stood 1.25 m tall and had a trapezoidal cross-section with a width at the hub of 36 cm and a tread width of 50 cm.

3.2 Phase I Results

Phase I of the Mars Ball Project was an attempt to prove that a multi-chambered tire would actually propel a vehicle. The capability of a Mars Ball was demonstrated, as well as the feasibility of a more elaborate project to fully test the abilities of this type of propulsion system. The completed Phase I Mars Ball is shown in Figure 3.2.

The vehicle proved to be capable of climbing slopes of up to 24 degrees, somewhat lower than the expectation of 35 degrees based on theoretical calculations for an ideal situation (see Section 2.3). The vehicle climbed slopes essentially by rolling on the rim of the hub and using a rearward sector to turn the tire without raising it off the surface by more than several centimeters. The forward sectors were deflated about one quarter turn before they reached the ground. The bags were thus partially compressed against the hub by the time they made contact with the slope (Figure 3.3). All propulsion was done by the one rearward sector. When inflating, this rear bag tended to be filled in the upper portion first. This mode of inflation produced a largely tangential force on the hub, providing a paddle-wheel effect and causing it to roll up the slope with very little tendency to lift off the surface in spite

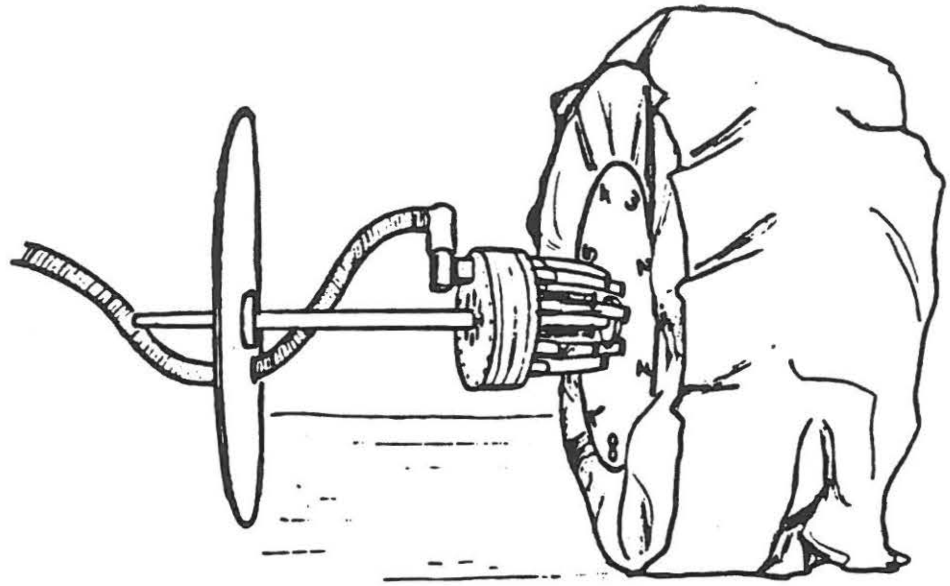

Figure 3.2. Completed Phase I Mars Ball. Pressurized air is supplied by an off-board compressor through the tube running off to the left.

of the light weight of the wheel. The two points on which the tire weight rested were the outer portion of the rear sector and the lower edge of the hub (or the deflating sector immediately underneath it). The sectors remained well placed in both the tangential and lateral directions, with each partition of the envelope being at or very near its proper radial orientation.

Correct placement of the sectors was facilitated by their relatively short length in relation to the hub, and by the presence of the outer envelope. Being comparable in length to the hub width and circumference, the bags were approximately spherical in shape and could not therefore become significantly displaced from their optimum positions. The outer envelope provided a further degree of control by augmenting the connection between the sectors. In order for any individual sector to become seriously misplaced before or during inflation, it would have had to pull on the envelope and thus shift other sectors as well. Their tendency to remain radial was great enough in relation to the weight of the tire to produce motion of the hub

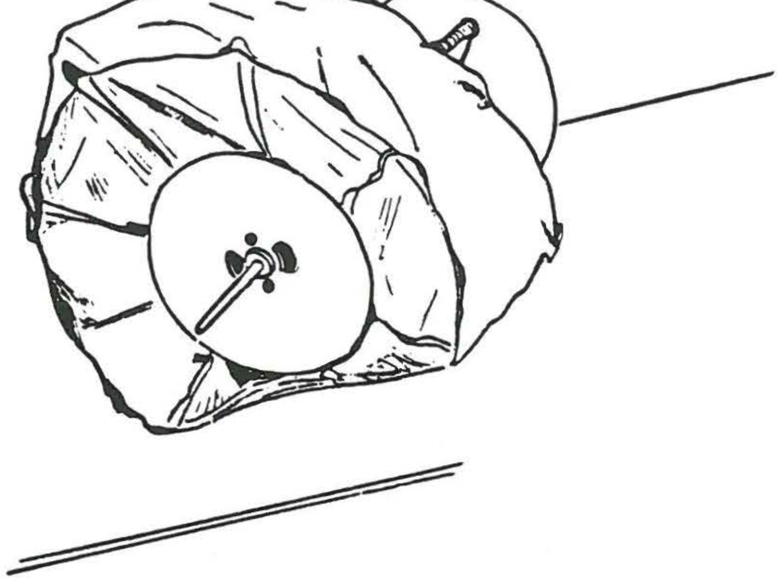

Figure 3.3. Slope-climbing by Phase I Mars Ball.

rather than spiralling or buckling of the bags.

The Phase I prototype was tested on a variety of rectangular obstacles. The largest obstacle the wheel could consistently negotiate was 0.15 m high, and even this capability depended in certain instances on having the correct placement of sector boundaries with respect to the obstacle. The other standard obstacle used was a human volunteer (torso, 0.15 m x 0.5 m) which again was successfully climbed if the sectors were properly positioned. This confirmed approximate obstacle limits of 25% of the vehicle radius, and 50% of the sector length.

The vehicle surmounted obstacles in much the same way it climbed slopes, that is by rolling on its rim and using the rearmost sector for propulsion. The act of inflation rolled and occasionally slid the hub to the summit of the obstacle. After ensuring that forward sectors were sufficiently inflated to break the fall, the vehicle was rolled off the obstacle.

Slope-climbing abilities of the vehicle seemed more than adequate, but the obstacle performance left room for improvement. In particular, it was extremely difficult to climb slopes with obstacles and other non-standard slopes such as staircases. The limiting case occured when the leading sector tended to push the vehicle downhill as it filled. The outer envelope which had placed the sectors perfectly during slope climbing actually became an impedement to obstacle negotiation; the tension between the rearmost inflated sector and the obstacle pulled most of the sector below the obstacle. This caused most of the force of inflation to be directed backwards. If the sectors had been independent, the force of inflation would have been primarily radial, allowing the vehicle to climb over the obstacle. We concluded that there was a tradeoff between slope-climbing and obstacle-climbing capabilities, and decided to design the next prototype with independent sectors.

A second design change, intended to facilitate applying the force in the desired direction, was to use twice as many sectors. We also decided to make the next model larger, two-wheeled, and computer controlled in order to better simulate travel on Mars.

4. PHASE 2 VEHICLE

4.1 Major Design Changes

In the design of the second generation prototype several fundamental design changes were made. The number of sectors per hub was increased, the sectors were lengthened and were not attached to their neighbors. More sophisticated control systems and air flow controls were adopted. Finally the overall scale of the vehicle was increased. This chapter describes the design and construction of each aspect of the Phase II Mars Ball. Lessons learned in the construction and early operation of the vehicle are related as they pertain to the detailed design. The performance of the Phase II vehicle is described in Chapter 5, while major problems and recomendations for a third generation Mars Ball are discussed in Chapter 6.

4.2 Hubs

Each of the two Mars Ball wheels consists of a hub surrounded by inflatable sectors. The hub (Figure 4.1a) consists of two 1.3 m diameter plywood circles attached to either end of an octagonal plywood cylinder which is 1 meter long. An assembly of radially arranged valves is mounted on the outside of each hub (away from the central payload). Mounted on the axle side of each hub (Figure 4.1b) are a blower (used to provide the high pressure air reservoir), and a small computer (used to control the valves). These components occupy small niches within the hub. Finally, inflatable sectors or airbags are mounted on the perimeter of each hub through the use of an airtight seal.

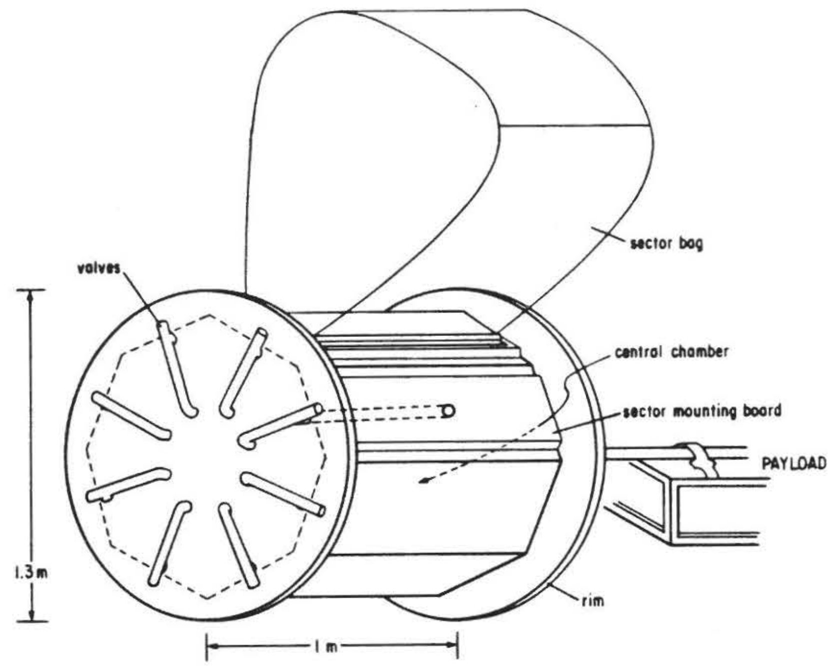

Figure 4.1a. Schematic of Phase II hub construction.

4.2.1 Hub Construction

Central to each hub is an airtight, high pressure (50 mbar) chamber constructed of eight rectangular plywood sections mitre-jointed to make an octagonal tube 1 meter in diameter and 1 meter long. This tube is then capped by two circular plywood disks 1.3 m in diameter. The overall dimensions of the hub were determined by the width of standard plywood sheeting and the width of the elevator door opening used for transporting the Mars Ball from its basement work area to the outdoors. All wooden structural members forming the central cylinder were given two coats of varnish to minimize air seepage and all butt-joints were sealed using Plastic Wood. The hub was then reinforced with a set of thirty-two threaded steel rods, running from disk to disk around the perimeter of the central tube, which can be adjusted to maintain tension on the hub. Finally, foam padding was cemented to the interior of the central chamber as a means of muffling blower noise.

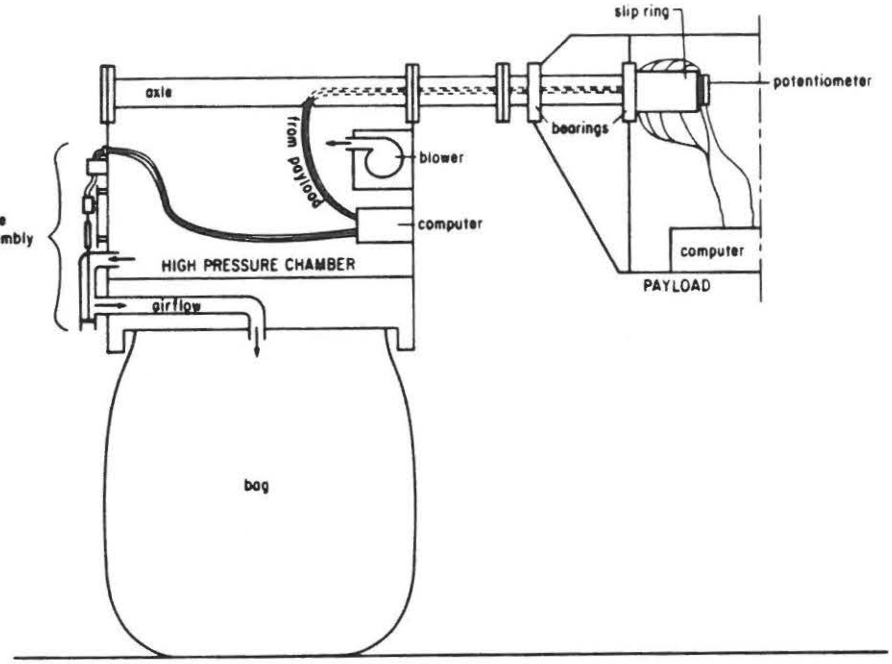

Figure 4.1b. Profile through Phase II hub and axle.

Sixteen mounting boards, of 6 mm plywood, 25 cm wide, extend between the disks near their outer edge. These boards have a central 7.5 cm hole through which passes the PVC tubing carrying the airflow. Sectors are attached to the exterior face of these boards by means of aluminum bars which squeeze the sector's vinyl material against self-adhesive weather stripping mounted on the board. The bars are held in place by screws which run through the bar, sector material and weather stripping and tighten on T-nuts in the mounting board. Problems encountered with maintaining air tightness at these mounting boards are treated in Section 4.3.1 dealing with the inflatable sectors.

Two rectangular cutouts were made in the interior disk of each hub and aluminum boxes fitted to them. One box contains the hub computer. The second box contains the blower, a commercial high volume impeller, which supplies pressurized air to the central hub chamber. Both boxes are sealed around their edges with weather stripping. Pressure is limited to a maximum in the two hubs by means of adjustable relief valves located adjacent to the blowers. Current operating pressure is 50 mbar.

Thirty-two 7.5 cm holes were cut in the outer plywood disk of the hub to accommodate the air supply plumbing. The holes are arranged in pairs, one giving access to the central pressurized chamber and the second, radial to the first, opening into the hub interior between the central chamber and the sector mounting board. Sixteen such hole pairs are arranged circumferentially around the outer face of the hub. Air supply passes through the holes, using a threaded pipe connector sealed against the hub by neoprene rings tightened against the inside face of the hub disk. For each pair, the radially interior threaded section then connects the valve assembly with the central chamber. The outer tube, connecting the valve assembly with its sector, runs through the outer disk, between the pressurized chamber and the mounting board and then turns at an elbow to go through the mounting board against which it sealed, again using neoprene rings. The short section of pipe extending into each sector is capped by a sleeve which has had small vents drilled through its sides to prevent the airflow from being cut off should bag material become folded against the mouth of the pipe.

Valves control the flow of air. Upon commands from the computer, the valves direct the flow of air through the plumbing system. The present vehicle has sixteen valves mounted radially on the outer face of each hub. Each valve is mounted to a plastic base plate, which in turn is mounted to the plywood disk of the hub by a series of screws (Figure 4.2). Two large holes in this base plate allow two branches of an airflow tube to access different reservoirs within the hub. One branch of the tube accesses the high pressure chamber of the hub, while the other accesses the section of the hub which leads to a bag. The third and final corridor of the tube leads to the open atmosphere.

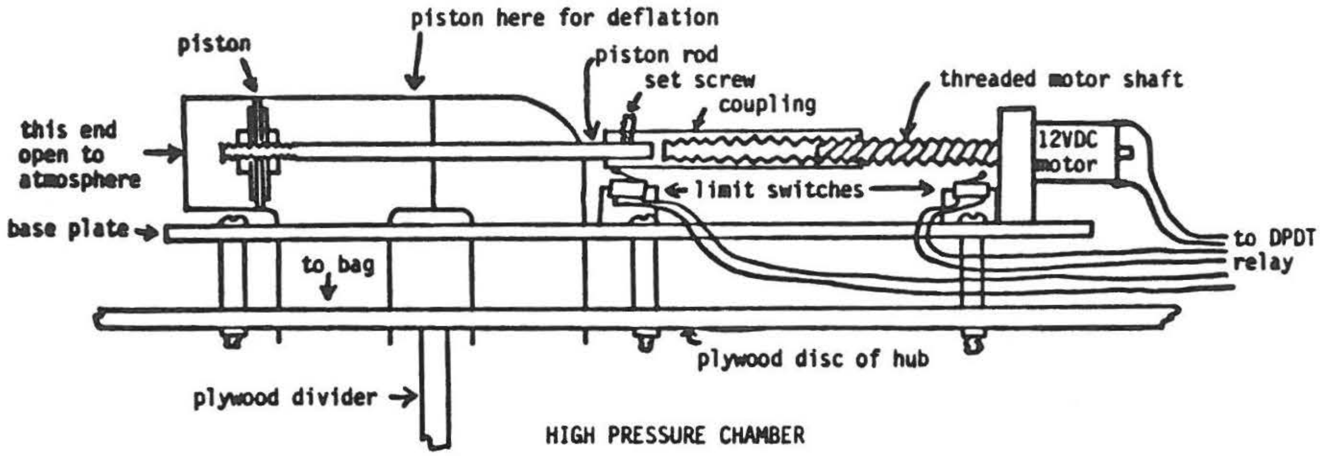

Figure 4.2. Valve assembly for Phase II Mars Ball.

The elbow of the tube faces toward the center of the hubs surface. This elbow has a small hole drilled in it, through which a thin steel rod is allowed to move. Within the tube this rod is connected to an airtight piston. The pistons are constructed of circular foam wafers cut to conform to the interior of the PVC piping and secured between two thin metal disks, slightly smaller in diameter, with the whole sandwich being held in place between two nuts at the end of the rod. The position of the piston determines whether inflation or deflation will occur. The other end of the steel rod is connected to a threaded coupling by means of a set screw. The threaded coupling is then driven, through the use of a 12V DC motor, by a threaded motor shaft causing the piston to move. When the threaded motor shaft turns clockwise, the piston moves away from the motor, and the air flows from the high pressure chamber to the bags. When the threaded motor shaft turns counter-clockwise, the piston moves back in toward the motor, and the high pressure chamber is isolated. The bag is now open to the atmosphere and therefore deflates.

The piston only has two positions; one for inflation, and one for deflation of the bags. The movement of the piston is stopped by two limit switches; one to stop the piston when it travels from inflate to deflate position, and one to stop it when it travels from deflate to inflate position. These switches are triggered when the front edge of the coupling, which is of greater diameter than the rod, physically presses down upon a springed portion of the limit switch. These limit switches are connected by wire to the motor through double-pole double-throw (DPDT) relay switches. Thus, when a limit switch is triggered, the DPDT relay is thrown, the motor stops turning, and the motion of the piston is stopped. In addition, the motor is now set to move in the opposite direction when the next command is received from the computer. Fuses were added to the system as a means of protecting the motor from possible strain.

4.2.2 Hub Performance and Modifications

In general the hubs and all their attendant hardware performed their assigned functions adequately. The primary function of the hubs was to provide the structural support and platform for the various subsystems involved in driving the vehicle. To this end they were constructed more with an eye toward structural integrity rather than toward weight and power requirements.

Structural problems with the hubs were few, being limited to occasional failure of some of the original bag mounting boards and disconnection of internal air supply plumbing. The original bag boards were constructed of low grade plywood, and under the repeated stress of inflation cycle tended to fail by either splitting or more frequently by allowing the T-nuts used in mounting the bags to be drawn completely through the board. Replacements for failed boards were made of a more rugged grade of plywood and these replacements have thus far proved adequate.

Connections between the various sections of PVC tubing used to route the air supply were of the threaded-screw variety, and occasionally, especially where the connection was being made through some thickness of plywood, as in passing through the hub walls or bagboards, there would be insufficient threads available to make a secure connection. The immediate remedy employed was simply to use the longest fittings available from our stock, and no further problems were experienced. In addition the size of the piping used places a limit on the speed with which air can be supplied to and vented from the sectors. In particular, in the absence of any active deflating scheme, the current limiting factor in the overall speed of the vehicle is the length of time necessary for a given sector to deflate.

The various subsystems within the hubs also performed their tasks adequately. The blowers supplying the pressurized air, operated continuously for several hours at a time without overheating or other failure. The volume of air delivered by these commercial units was sufficient with the current vehicle size to meet the 1 km/day velocity requirement for a Martian rover. No attempt was made to filter the incoming air of any particulates and the effect on the efficiency of the blowers by such a restriction in intake was not assessed.

The orientation of the rod assembly, as well as the positioning of the limit switches, is crucial to the performance of the valve system. If the rod is not directly on a line with the coupling rod and threaded motor shaft, substantial strain can be borne by the motors. This misalignment can cause substantial friction, and requires the motor to work harder than was intended and to draw excessive current. Several motors were burned out before fuses were installed. Eventually alignment errors were corrected and problems in this area became minimal.

The positioning of the limit switches is important because this directly determines the position of the piston. A good seal is necessary for optimum efficiency in directing air flow. In addition, the limit switches have occasionally not properly triggered, often as a result of being too far from the coupling. Thus the motor is told to continue pushing the piston, while the piston has nowhere to go. Again, strain and potential damage to the motor results. However, problems in this area have been minimal, and both problems should be eliminated with careful and precise vehicle construction.

One of the largest single factors in the current limits on the capabilities and efficiency of the Mars Ball is the weight of the vehicle. As noted, components were chosen for their ready availability and strength with weight being only of secondary concern. Each hub, for example, weighed in excess of 180 kg, and in the peculiar motion of the Mars Ball this large mass is lifted with the inflation of each sector during motion. The large mass of the vehicle contributes to its large power demands, currently approximately 1600 watts, as does the lack of any power cut-off on the blowers. The blowers now operate continuously with excess air flow being dumped overboard through pressure relief valves mounted in each hub. In addition all air which has been pressurized and delivered to a given sector during inflation is likewise simply vented to the ambient atmosphere after a single use rather than being recycled to the central storage chamber. Chapter 6 discusses these problems and possible resolutions that could be employed in a third generation vehicle.

4.3 Sectors

As discussed in Chapter 3, the Phase I wheel had some difficulty negotiating stairways and slopes on which obstacles had been placed. The performance in these cases seemed to sometimes be limited by the fact that sectors were pulled to undesirable locations by their inflating neighbors. It was also evident that a tire with more sectors would be more likely to overcome such terrain as well as to climb steeper slopes, based on the analysis given in Section 2.3. For these reasons the tires of the Phase II vehicle were designed to each have 16 mechanically independent sectors. The length of the sectors was desired to be as long as practical in order to maximize the slope climbing abilities. A vehicle with large tires would also publicly emphasize the expected large size of an actual Mars version and the consequent scientific and logistical advantages to be gained. A tire with relatively long sectors in relation to the hub diameter would provide this large vehicle size and also would illustrate the fact that the collapsible Mars Ball design will fit in a relatively small payload volume.

4.3.1 Sector Construction

The Phase II sectors were originally envisioned to each consist of an inner airtight bladder and an outer envelope, similar to the Phase I tire. The outer envelope would protect the bladder from punctures and abrasion and would also relieve the tension on the bladder due to the operating air pressure. This "tube-type" construction would have separated the functions of air containment and mechanical support. The bladders were thus chosen to be commercially available 4000 liter, 3 mil polyethylene bags with the open end connected to the air plumbing at the hub. The material chosen for the outer envelopes was burlap, due to its availability and high tensile strength.

Attempts to construct a reliable working sector of this type were unsuccessful, however. In practice, the corners of the burlap envelope were not filled by the polyethylene bladder as intended. The tension due to the working overpressure (i.e., above atmospheric pressure) of 50 to 90 mbar thus had to be carried by the bladder in this corner region rather than by the burlap. Since the materials had been chosen under the assumption that all tension would be transferred to the burlap, the polyethylene bladders were not sufficiently strong and consequently burst along one of their seams near this corner.

Following several bladder ruptures of this type, experiments were begun on a "tubeless" bag, in which one layer of material would perform all mechanical and air containment functions. Test bags approximately 1 meter in length were constructed of fabrics chosen for their strength, durability, and apparent air-tightness. Various heavy duty nylon fabrics, such as those used in backpacks, were tried, but were found to allow too much air leakage through the weave of the fabric. The material finally chosen for the sectors was a nylon reinforced vinyl laminate which was adequately strong and also impermeable to air.

For the testing done to date, the vehicle was operated on fairly smooth surfaces, so burlap envelopes, considered as abrasion protection for the vinyl and as a rough surface to provide the necessary traction, have not been implemented.

Two bolts of the vinyl laminate, one each of red and white, were purchased. Each bag was comprised of three panels cut from the vinyl. Since a long sector was considered to be best for enabling the vehicle to climb slopes, a bag length of 2 m was chosen. The width of each sector is 1 meter. Each sector was 2 m long when fully inflated, tapering from a perimeter length of 1 m to 23 cm at the hub. Each wheel, in this initial configuration, was 5 m in diameter when fully inflated. Enough panels were cut from the vinyl to make 16 bags for each wheel plus 8 spares. We assembled the first bag by sewing together the three pieces of vinyl on a standard sewing machine. The pieces were sewn with heavy-duty bonded polyester thread with 2 stitches per centimeter. The seams were doubly sewn to provide increased strength. Given the difficulty of making such a seam and the time involved in sewing 40 bags in this way, we contracted the job to the University Upholstery Shop.

After being sewn, the seams of each bag required further sealing in order to obtain sufficient working pressure from the existing blowers. Two different sealing techniques were employed. The first was used on the straight sections of the seams. A patch of the same nylon reinforced vinyl was attached to the inside face of the seam. The patches were cut in the form of strips approximately 8 cm in width in order to allow sufficient area for adhesion on each side of the seam, and also to reduce the possibility of air leakage through any uncemented gap between the patch and the bag material. The patches were cemented to the bag using a commercially available vinyl cement containing toluol, methylethyl ketone, and acetone (HH-66 brand, R-H Products Co., Inc., Acton, Mass.). Cement was applied to both bag and patch and allowed to dry for 2 to 5 minutes before the patch was applied. The patch was then clamped in place for a minimum of one hour. The corners and tapered portions of the seams near the open ends of the bags were sealed with a liquid vinyl repair compound containing tetrahydrofuran, butanone, and cyclohexanone (VLP brand, PDI Inc., St. Paul, Minn.). This liquid was applied from a tube to all three faces of the seam. Originally, it had been planned that all seams would be sealed with the liquid vinyl repair compound. However, the first bag of this type to be constructed was found to be significantly weaker immediately adjacent (i.e., within 2 mm) to the dried vinyl repair liquid, and this sealing method was retained only for the corners and extreme ends of the bags, where the tension was significantly less.

After sealing was complete, each bag was allowed to dry at least overnight before air pressure was applied. When all seams were sealed and dry, each bag was tested under blower pressure to verify that leakage had been sufficiently reduced and that all portions of the bag would withstand the tension produced. The criterion for certification of a bag as useable was that it maintain an overpressure of 90 mbar or greater. Most bags were able to hold pressures of 95 to 110 mbar during these tests. The latter pressure was the maximum attainable from the chosen blowers. The bag testing and certification was performed on a test unit which had originally been built in order to determine the optimum dimensions and placement of the various working components of the hub. The test unit was effectively one eighth of a hub in all major aspects and important details. It was used for bag certification because of its convenience, and also because certification of the first 16 bags was done before the first hub was completed.

The bag stitching proved more than adequate to handle all stresses imposed by the bag pressures, and was in fact stronger than the nylon-reinforced vinyl of the bag itself. After repeated use, the material along the inner stitch occasionally stretched until the original needle holes were 3 mm or more in length. The stretching occurred most often along the outer half of the straight, patched portions of the radial seams. This is thought to be due to the fact that the tension in the material is proportional to bag circumference, which is largest in this area. However, leaks did also develop less frequently along other portions of the seams and even in the midst of the fabric itself. The strengthening of the seams due to the added layer of patch material was apparently offset by the weakening effect of the vinyl cement.

The decision to proceed with a tubeless sector construction necessitated the design of a bag mounting system which was essentially airtight and also capable of anchoring the sectors to the hub. Experiments were made with a variety of fastening arrangements. The one found most promising was a system in which the edges of the open end of the bag were clamped between two stiff lamina in a plane perpendicular to the long axis of the bag (Figure 4.3). This arrangement was chosen because of its ability to hold the bags firmly in place and also because it would fit conveniently between the disks of the hub.

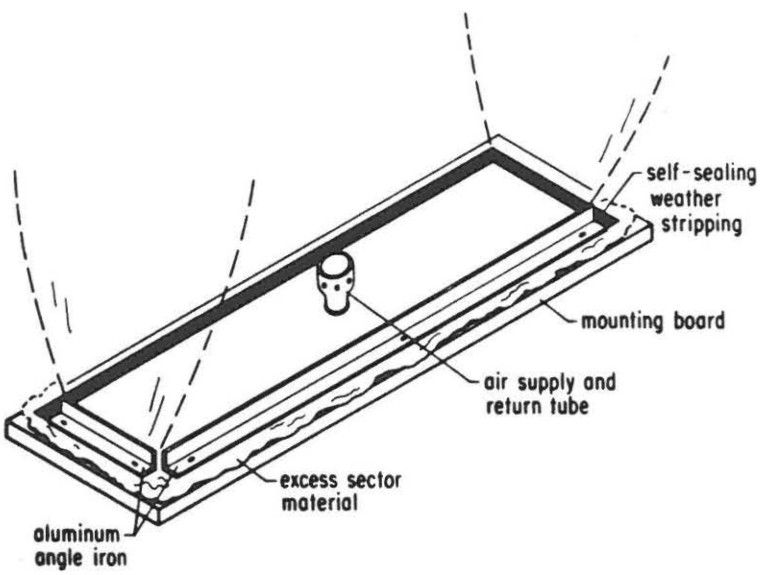

Figure 4.3. System for mounting inflatable sectors to the hubs.

The base for the mounting of each bag was a 13 mm by 86 cm by 20 cm piece of plywood, which was anchored at its ends to aluminum angles on each of the disks. The upper half of the clamping arrangement was made of 25 mm aluminum angle, 3 mm thick, with clearance holes drilled for machine screws which fastened it to the baseplate. Aluminum angle was chosen for its stiffness, which was intended to prevent leakage due to separation from the base plate. It was also chosen for convenience of production by the University of Arizona Instrument Shop. Four pieces of angle per bag were required, corresponding to the two long and two short edges. The long pieces were 74 cm in length with four clearance holes for machine screws at 18 cm spacings. The short pieces were 18 cm long with a central clearance hole for one of these machine screws. Their upward projecting corners were removed to avoid injury to bags or persons. An airtight seal was insured by including a layer of 5 mm thick and 38 mm wide foam weather stripping between the bag material and the plywood base plate.

The inside dimensions of the rectangle formed by the mounting angles were thus 13 and 74 cm. At an operating pressure of 90 mbar, the resulting force between the bag and the base plate is approximately 845 N. This force from the bag was sufficient to pull the ends of the long mounting angles away from the base plate far enough to cause significant leakage. To eliminate this problem, a machine screw was added near each end of these angles, reducing the free length there from 9 cm to 25 mm. These additional fasteners were successful in reducing the leakage to tolerable levels. The short angles continued to be held down at only the one central point, but leakage under them was never significant. The large force on the bag also tended to pull it out from under the angles so that the holes through which the machine screws passed were exposed, thus producing further leakage. The remedy for this problem was adequate tightening of the machine screws. Because the plywood of the base plate was compressible, the machine screws had to be tightened before each field test of the vehicle. These repeated tightenings caused weakening of the plywood and occasionally complete structural failure. A partial solution to this problem, using higher quality plywood base plates, is discussed in Section 4.2.

Once the bags were mounted on the hub they were removed only if in need of repair. When the vehicle was not in use the deflated bags were individually rolled up, starting from the outer end and rolling in toward the hub. The "furled" bags were fixed to the hub in this position with 2 bungee cords. Metal hooks at either end of these cords fit into holes in the mounting angles. This compact configuration made transporting and storing the vehicle easier. Also, when the vehicle was operated with less than 16 sectors "active", the unused bags were simply kept furled and so did not interfere with performance.

4.3.2 Sector Performance Issues and Modifications

The performance of the vehicle with the 2 meter bags was problematic (see discussion in Chapter 5). In straight rolling and even in standing upright the vehicle was unstable. Upon listing to either side, it would remain unbalanced, seeming to have no ability to recover from this situation. Some of the solutions which were proposed included various means of fixing adjacent bags to one another. When inflated, adjacent bags touch at their midsections but diverge at the outer ends: they assume a cylindrical shape rather than the ideal wedge shape we had intended in our design. Figure 4.4 illustrates the actual shape as compared to the ideal shape. The outer corners of adjacent bags were as far apart as 45 cm. It was believed that vehicle stability would improve if the divergence of adjacent bags could be decreased (thus increasing the area of contact between bags).

One approach to this problem was to lace the bags to each other along their (radial) adjacent seams. Grommets were put into the strips of seam allowance material. The spacing and number of grommets was varied in several tests. To lace

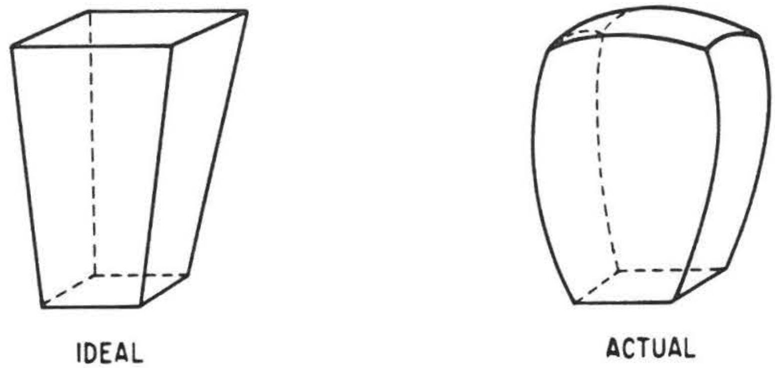

Figure 4.4. Ideal vs. actual shape of the inflated sectors.

the bags, we tried elastic bungee cord as well as a non-elastic cord. This method did reduce the divergence of the bags but the force required to keep the bags together was so great that the material holding the grommets was strained to the point of failure. This led to the following approach: sleeves made of burlap were placed over each bag and the grommets were put into the burlap. The idea was that the burlap would withstand the strain better than the bag material did. The sleeves went from the narrow end of the bags near the hub, to about two-thirds of the way up. In tests with the sleeves in place about inflated bags, the sleeves showed a strong tendency to slip from their original position down to the narrower part of the bags. To correct this the sleeves would have had to be fastened somehow to the bags, and this would have put stress back onto the bags. The sleeves were also not strong enough to hold the sectors sufficiently close together, even when the grommet attachment to the burlap was reinforced with a strip of high strength webbing. For these reasons the sleeve idea was not pursued further.

Another idea to increase vehicle stability was to shorten the bags. This was first tested on a single bag. The lower edges were folded under so that the length was reduced from 2 m to 1.3 m. New holes for the mounting screws were punched into this folded edge and the bag was re-mounted. This shorter bag, when inflated, was significantly more resistant to lateral deviation than the 2 m bags. Possible reasons for this improved performance are cited in Chapter 5. The test was convincing enough to warrant shortening all the bags. As with the test bag, the edges of the bags were simply folded under to reduce the length. Aside from the holes for the mounting hardware, no cuts were made in the bag material. This left open the possibility of returning to 2 m bags if desired. The holes could be patched and the edges unfolded to restore the full bag length. This configuration meant that the diameter of the wheel was 4 m instead of 5 m. Since the outer dimensions of the bags were unchanged, the reduction in circumference had to accommodated by reducing the number of bags.

4.4 Axles and Payload

The two hubs are joined by a central unit consisting of the payload section and a pair of axles. This unit also houses the payload computer with its power supply, and has sufficient space for scientific instrumentation. It was designed largely for strength, based on an analysis of the strength required were the vehicle to fall from an end-on position (ignoring the fact that the hubs themselves were constructed of plywood).

4.4.1 Payload Construction

The payload constists of a box-steel framework with two axles top mounted so that the payload section hangs freely beneath them (Figure 4.5). The payload itself is 1.5 m long, 0.45 m high and 0.4 m deep. Dimensions were chosen on the basis that the payload just touch the ground when the hubs were deflated. The initially chosen height of 0.5 m was shortened to insure that the payload fit comfortably within the cross section of the hubs. This extra height margin allowed for the addition of casters to the four corners of the payload to facilitate transport when disconnected from the hubs. The four long corner pieces are 3.2 cm square steel tubing with 3.0 mm walls. All other pieces have 1.7 mm walls. Plywood sheets are included as front and back panels. These were designed for quick and easy attachment and to provide some protection from blowing dust.

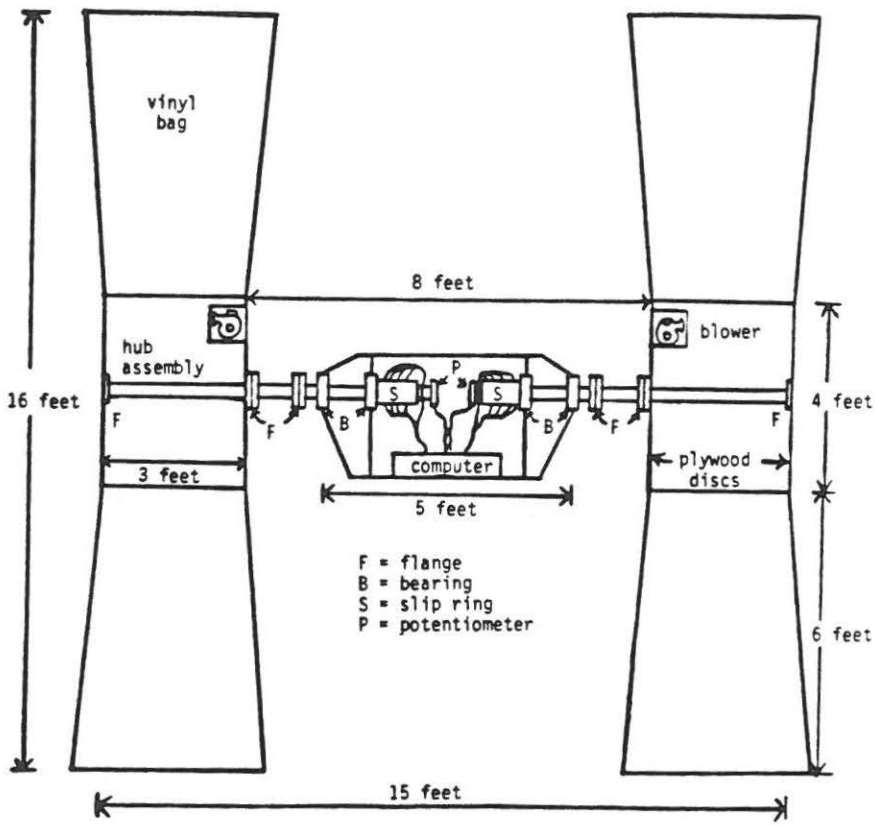

Figure 4.5. Schematic diagram of the Mars Ball showing central payload and attachment to the two wheels.

The axles connect with the payload through two saddle bearings mounted to the upper payload members at either end of the payload. These allow the payload to be suspended freely beneath the centerline of the hubs. Different axle sizes considered were 7.6 cm and 10.2 cm outside diameters with 2.5 cm and 1.3 cm wall thicknesses. The axles finally chosen are in sections fabricated from 7.6 cm by 1.3 cm tubular steel. Short, 0.4 m, axle sections connect the saddle bearings and hub.

Flanges, 14 cm in diameter and 9.5 mm thick and tapped for 9.5 mm bolts, are welded to the ends of the section as well as the hubs axle portions of the main bearings. These permit disassembly of the vehicle into its three main components, the two hubs and the payload. The short axle sections have 5 cm holes drilled in the sidewall for passage of the electrical connecting cable from their interior (at the payload end) to the exterior (at the hub end). The cable passes through the core of the axle within the saddle bearing and terminates at a slip ring assembly inboard of the bearing. This assembly supplies the power and computer communications between the payload and the rotating hubs. Plexiglass housings protect the slip rings from dust. A potentiometer is attached to the central spindle of each slip ring assembly for determination of the position of the hub relative to the payload.

The Physics Department machine shop constructed the payload and axles, which upon completion had a total mass of 80 kg. The mass was not a significant design criterion, but was considered reasonable as an actual payload would be required to carry more equipment. The length of the payload was determined mainly by a desire to maintain the overall aspect ratio of the Mars Ball at unity, and also by the limited steel tubing available to manufacture the axle extensions.

4.4.2 Payload Performance

The payload did its job satisfactorily. Originally, the axles were not quite parallel (they pointed slightly upward, away from the payload). This was corrected by inserting 1.6 mm shims under the saddle bearings. There were a few other minor problems as well. The payload tended to drag on the ground when the vehicle was going uphill, but this was only of serious concern when the casters remained attached. Additionally, some problems occurred when the slip rings failed to make continuous contact, causing computer malfunctions. This problem seemed to diminish in frequency once the slip rings began to rotate. Computer problems are discussed more fully in Section 4.5.

It was originally feared that the torque generated by the weight of the payload might cause the bearings to bind, so that the payload would no longer hang freely, but rather turn with the hubs. There was no evidence of this in testing. The payload and axle system is probably much stronger than required, but this cannot be determined short of destructive testing.

4.5 Computers and Control Circuitry

The design of the control circuitry was intended to imitate an actual rover in concept but not in materials. In other words, we chose readily available components and built a rover with "mission control" and on-board computers. The details of the implementation are not critical, but the Mars Ball concept does force certain constraints on the control system which are described in the following pages.

Simply stated, the computers direct the motion of the vehicle by controlling the position of the valves mounted on the hubs. (See Section 4.2 for a discussion of the valves.) An operator at the remote control computer issues a command, and the rover acts on that command, and relays information back to the operator.

4.5.1 Hardware and Circuitry

An interesting problem is posed by the design of the vehicle. The payload hangs below the axle, and the two wheels must be free to rotate independently. Therefore, the commands (and the electrical power to carry them out) must be transmitted from the payload through the rotating axle to the hubs. This is performed by slip rings, described in Section 4.4. Rather than provide a rotating connection for each valve (16 in the original design) and every other function the hubs might carry out, we decided to install independent computers in both of the hubs. These computers would communicate with the payload computer through the slip rings. This reduced the required number of rings dramatically: the serial

RS-232 communications protocol required only three lines; two more were needed to supply voltage to the valves, and two for blower power. In early testing, the flexing of the vehicle during motion resulted in slight variation in the force on the electrical contacts on the slip rings which occasionally caused momentary hub power dropouts and computer crashes. A more careful design, which isolates the electrical connections from the mechanical mounting, should eliminate the problem. Our solution was to devise a software check for power failures and install battery backups on all on-board computers.

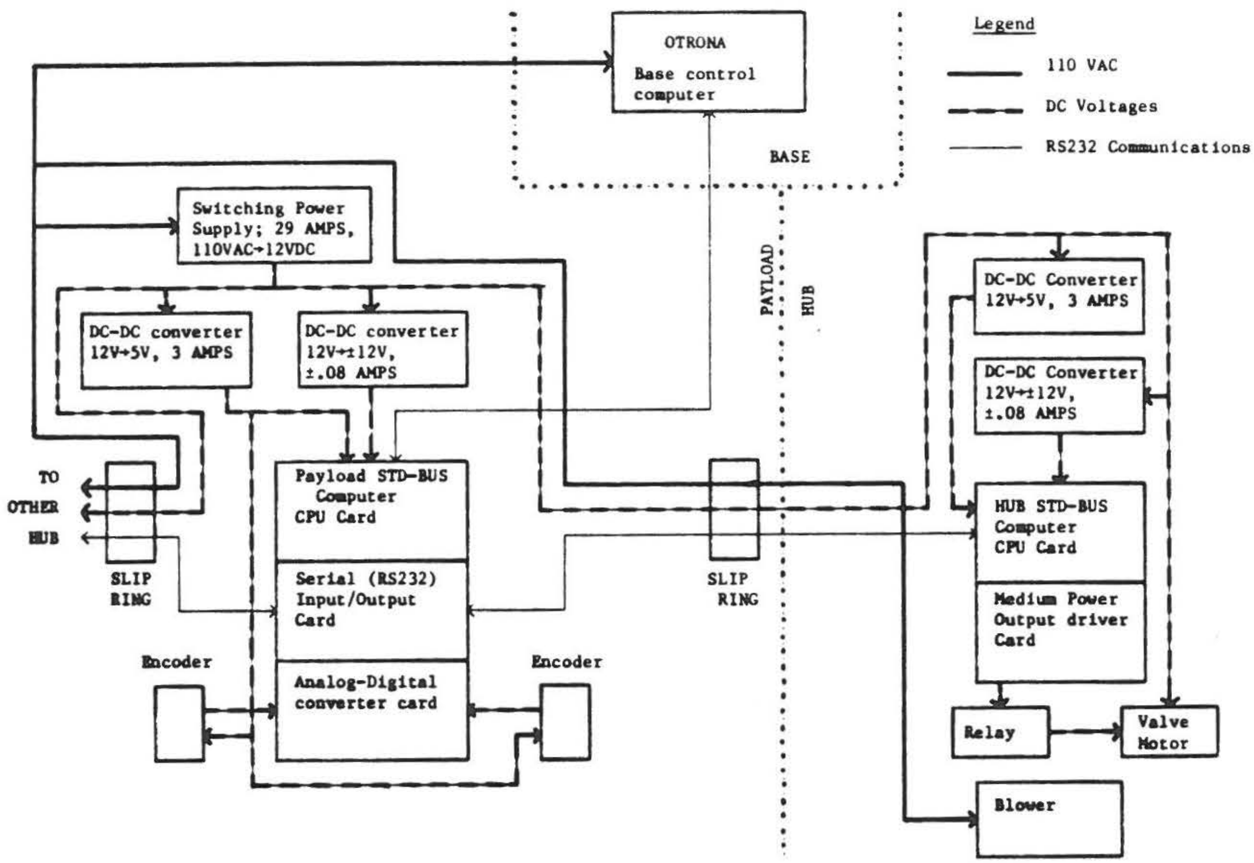

Figure 4.6. Power and communications distribution circuitry.

The block diagram for the computer design is shown in Figure 4.6. There are four computers: "mission control", the payload computer, and the two hub computers. In operation, a command is entered at the keyboard of the control computer, and is transmitted to the payload computer. Here the command is converted into instructions for the individual hubs, and these are sent to the appropriate hub. The hub computers decode the command and move the valves by switching relays. In addition, the payload computer is continually monitoring the rotation of the wheels by means of a potentiometer and analogue-to-digital converter, which encodes the orientation of the hub with respect to the payload hanging vertically downward (except for a very slight frictional lag). This information, which is relayed to the control computer on request, could be used to gauge the distance travelled by the rover as well as its speed. We also built two hand-paddles with banks of switches for manual control in emergencies. These bypassed the computers and were attached to the individual hubs by 25-conductor cables.

4.5.2 Software and Control Algorithms

Programs were developed on the operator's computer, then downloaded to the payload and hub computers for testing. Final versions of the on-board programs were loaded onto ROM chips and installed in the three vehicle computers. The programming was done in low-level Z-80 assembly language for ease of interfacing the computer with external devices such as relays. The use of three on-board computers reduced the number of slip-rings needed but increased the software requirements. Much of the computer code was devoted to communications, error checking and crash recovery. This consumed a fair proportion of our programming time. The remainder dealt with controlling the valves, monitoring the wheel orientation, and low-level decision-making.

In manual operation, the vehicle was controlled by individual commands to inflate or deflate a given sector on a given wheel. The wheel would rotate in response to the command, and at an appropriate orientation the next command would be issued by the operator. During the testing process, we determined the basic criteria for rolling on flat terrain. At the start of a cycle, the wheel rests equally on two inflated sectors in contact with the ground with the sector between them deflated. The forward of these is then emptied and the vehicle rolls ahead until the partition between the two deflated sectors lies almost directly below the payload, at which point the trailing sector is reinflated. For maximum stability, progress is alternated between the wheels. The critical angles at which deflation and reinflation optimally occur were programmed into a loop which issued commands, monitored the rolling until the proper configuration was achieved, then repeated the sequence. This "automatic rolling" is the first step toward genuine autonomous operation of the Mars Ball.

Future development would include an algorithm for climbing slopes, perhaps employing a strategy in which two sectors are deflated in the starting position and a third is emptied to initiate rolling. Slope and hazard indicators (some of the recommended enhancements discussed in Chapter 6) would permit the development of obstacle avoidance algorithms more sophisticated than the child's toy strategy of reversing direction when the rover fails to roll forward. The only motion sensor currently incorporated in the vehicle is a pair of potentiometers which measure the position of the hubs relative to the central payload. Sensors for determining motion relative to the ground are discussed in Section 6.1.

5. PHASE II TEST RESULTS

5.1 Introduction

The Phase II prototype was tested on the grounds of the University of Arizona during 1986 and 1987. During that time, the design underwent a number of evolutionary changes in response to field results. The end product was a vehicle which in most respects meets the mobility requirements for a Mars rover mission. The sections below discuss the individual mobility requirements and the performance of the Phase II prototype in its final configuration. In several cases, the modifications made to the Mars Ball are particularly illustrative of the capabilities and limitations of the Mars Ball design. Only intermediate design stages of this type are mentioned below. For the most important capabilities, namely slope and obstacle climbing, we compare and contrast the performance of the Phase II prototype with that of the Phase I prototype.

5.2 Stability

The greatest challenge in the design and testing phase of the Mars Ball was to find ways to enhance the lateral stability of the vehicle. Stability (Figure 5.1a) was the driving force behind most modifications made to the vehicle. In this section we discuss the effect each relevant design feature had on the stability, both dynamic and static, of the Mars Ball.

Perhaps the most obvious contributor to vehicle stability is the air pressure inside the inflated sectors (see Figure 5.1b). Air pressure contributes to the vehicle stability in three separate ways. First, the internal pressure seeks to restore the sectors to their greatest possible volume. Thus internal pressure of the sectors naturally opposes twisting or bending distortions which decrease the interior sector

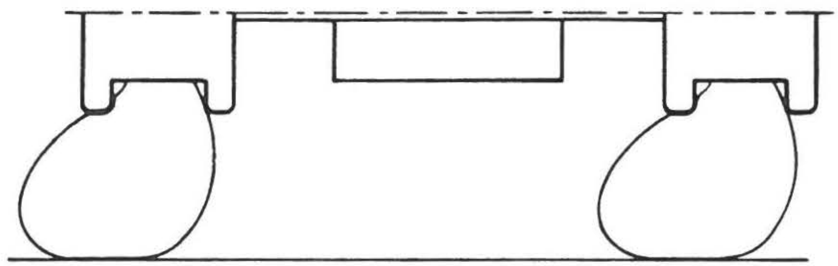

Figure 5.1a. Lateral instability experienced with the Phase II vehicle.

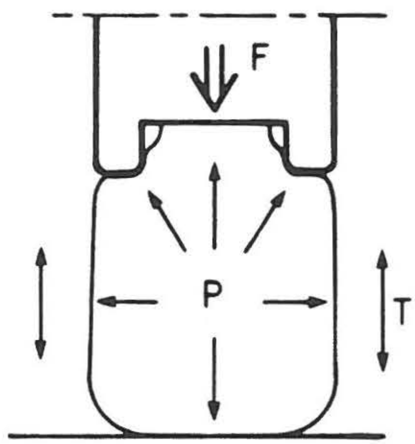

Figure 5.1b. Important forces affecting stability. The weight of the vehicle provides a downward force, **F**, opposed by the bag pressure, **P**. Bag tension, **T**, helps maintain bag shape.

volume. Also, greater internal pressure inflates the sectors more rapidly.

The second important contribution to vehicle stability is the tension produced in the bag material. The greater the internal pressure (once maximum bag volume has been obtained), the greater the tension in the walls of the sectors. When bag material is not under tension it is more likely to buckle and twist. At high internal pressures the sectors are rigid and provide much greater support and rigidity. The tension in the fabric due to the vehicle load is generally not equal in all directions; the higher pressure tends to equalize the tensions in the fabric. This higher, more even fabric tension especially helps prevent the Mars Ball from sagging over to one side atop floppy sectors.

Third, the internal pressure tends to force the sectors against the vehicle itself. If the vehicle does begin to flop over to the side, the bags must deform against the vehicle. As the bags begin to deform they produce a restoring force which acts to push the Mars Ball back in the opposite direction, thus stabilizing the vehicle. This stabilizing force is also a function of bag shape, discussed below.

Greater air pressure, however, is not the solution to all design problems. The vehicle's speed is currently limited by deflation time, not inflation time. Also, beyond a maximum internal pressure the sectors begin to fail as fabric tears and grommets, providing for bag interconnection, rip out.

Another important source of vehicle stability is the exact relative placement of the individual sectors on each wheel. Ideally, when fully standing the sectors should form an almost complete "tire" around each hub. If all the sectors are simultaneously inflated there is nothing to stop the Mars Ball from rolling downhill. Therefore the bottom sector directly beneath each hub is always deflated. The stability problems encountered in moving from this stable position are discussed in Section 5.3.

The sectors must not only be positioned properly to provide support, they must also provide support for one another. This implies that the bags must be interconnected in a way that maximizes mutual support. In the Phase II vehicle with the longer, 2 m bags there was a tendency for some sectors to be "squeezed" out from a wheel shape. Occasionally the sectors would almost form a wave pattern as alternate sectors deviated to alternating sides from a perfect wheel shape. In such instances the loads passed from one sector to the next, tending to squeeze sectors even farther out of alignment and ultimately destabilizing the Mars Ball. Several attempts at threading the outer sector edges with rope to align the sectors were attempted. While these measures helped somewhat, they did not solve the problem. The replacement of the original sectors with half as many shorter sectors essentially eliminated this problem.

The shape of the bags provides an important contribution to vehicle stability. In the field testing of the Mars Ball we found that short, stubby 1.3 m sectors provided significantly greater stability than the longer 2 m sectors. We attribute this enhanced stability as much to the actual *shape* difference of the new sectors as to other contributions of the shorter length discussed above. Since the shorter sectors were constructed by simply taking 0.6 m off the longer sectors at the open (or hub) side of the bag, the mouth of the new sectors was wider than before. This difference arose because the bags were designed to taper inward so that the footprint end was larger than the hub end. Hence the new sectors were not only shorter, but also fatter and more rounded near the connection with the hub (Figure 5.2). This meant that, much more so than before, when the bag bent or buckled it had to do so by forcing itself against the hub. The hub thus acted to constrain the new bags in a way that was impossible with the older design. Although an exact physical explanation for this behavior is elusive, the importance of bag shape was consistently demonstrated in both experiments and in the actual outdoor tests. We feel that one of the most important issues facing designers of a third generation Mars Ball would be evaluation of the performance of various bag shapes.

5.3 Rolling

The most basic test applied to such an unusual mode of transportation, after static stability has been achieved, is motion on flat terrain. Several major design changes were required before the Phase II prototype passed this simple test. In the end, the vehicle was able to roll at a speed of approximately 1 meter per minute. While this may sound slow (our implementation was definitely not optimized for speed) it nevertheless meets the minimum kilometer-per-day NASA requirement for a Mars rover. The section below outlines the rolling capabilities of the Phase

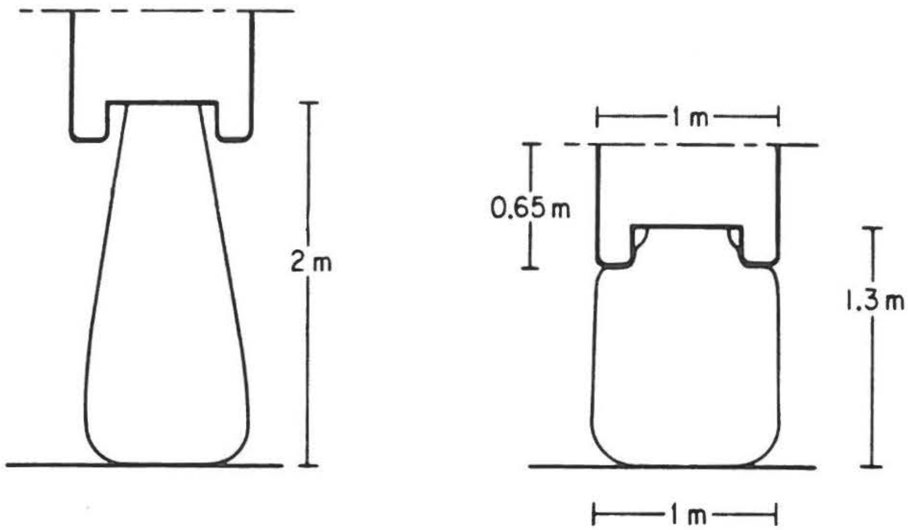

Figure 5.2. Comparison of size and shape of long 2 m and short 1.3 m bags.

II prototype in final form, and discusses the major design requirements needed to achieve them.

The rolling procedure is outlined in Section 2.3 (Figure 2.2). A wheel rolls forward 1/8 revolution by deflation of the leading sector and subsequent inflation of the trailing sector. We tested two types of inflation/deflation sequences. The first, as shown in Figure 2.2, alternates between one and two deflated sectors, and is therefore identified as "1-2 gap". This proved the most useful mode of operation, and it worked well both forward and backward. For a single wheel, the inflation takes about 30 seconds, and deflation another 45 seconds or longer.

The second sequence alternates between two and three sectors deflated. In "2-3 gap" mode, the vehicle stays closer to the ground, and spends more time and energy lifting and dropping the weight of the vehicle. This operating sequence was rarely used. With the current 8-sector design, no other distinct modes are possible (i.e., 3-4 gap) because the hub already touches the ground in 2-3 gap mode, so further deflations have no effect. Note also that a "0-1 gap" cannot be used: when no sectors are deflated, the wheel is round and can roll either direction without control. A 1-sector gap is required to keep the vehicle under control.

Lateral stability placed a limit on the rolling speed. In essence, the Mars

Ball stands on four footprints: the inflated sectors ahead of and behind the gap on each wheel. When a sector acting as one of these feet is deflated, it loses its rigidity and hence its ability to provide lateral support to the vehicle as a whole. In the simplest rolling mode, both wheels move simultaneously. But when the front "feet" of both wheels are simultaneously deflated, the front of the vehicle loses its lateral stability, and the whole vehicle shifts to one side or the other, depending on the slope of the terrain or the alignment of sectors. We therefore altered the rolling sequence to place one wheel half a cycle out of phase from the other, thereby avoiding simultaneous deflation of the front sectors. Thus the forward sector of one wheel was deflating while the rear sector of the other wheel was inflating; the two diagonally-opposite inflated feet provided sufficient stability. We therefore adopted the following routine for forward rolling:

Time	Control Action
0:00	Deflate Right Front
0:45	Inflate Right Rear
	Deflate Left Front
1:30	Inflate Left Rear
	Deflate Right Front...

Note that avoiding simultaneous deflations effectively lengthens the inflation time to 45 seconds; this slowed the vehicle somewhat. Had the deflation time been very short, the staggering of wheel phase might not have been necessary.

Early testing revealed a number of unexpected design requirements for successful rolling. The key to successful rolling is the correct placement of deflated sectors waiting for inflation. The completely independent sectors of the Phase II design did not meet this requirement; the deflated sectors fell out of alignment both in the plane of the wheel and perpendicular to the plane. As a result, inflation of these improperly placed sectors usually resulted in backwards or sideways motion of the vehicle. As rolling continued, the problem worsened to the point that most of the sectors were out of the plane of the wheel. To remedy this, we connected the corners of adjacent sectors with elastic cords made of surgical tubing (see Figure 5.3). These cords forced empty sectors to position themselves exactly between the edges of inflated sectors. This method of interconnection worked quite well for rolling, but proved inadequate for slope- and obstacle-climbing, as discussed later in this chapter.

The positioning of deflated sectors will also depend on the correct alignment of the inflated sectors. In the early testing period of Phase II, (16-sectors of 2 meters length on each hub) the vehicle encountered overwhelming difficulties positioning inflated sectors properly. The problem stemmed from the fact that each sector tried to occupy more than its share of the circumference of the wheel. The sectors were designed to have a rectangular cross-section; in practice, of course, this is not a natural shape for an inflated object. Each sector billowed out to a more circular cross-section, with a substantially greater width than the original rectangle. The extra pressure between sectors always forced the inflated sectors apart from each other; twelve sectors actually proved sufficient to fill the circumference of the wheel. With all sixteen sectors in use in early testing, at least five sectors in a row had to be deflated before any gap would appear; with this many sectors deflated and the remainder distorted out of their intended positions, rolling motion proved impossible. Further tests with only 9 to 12 evenly-spaced sectors in use showed more promise, but the lateral stability problems discussed in Section 5.2 proved insurmountable. The final design, with 8 sectors 1.3 m in length, positioned its inflated sectors very well.

5.4 Turning

The Mars Ball consistently demonstrated the ability to turn in place. By rotating the two hubs in opposite directions, the vehicle simply rotates any desired amount about a vertical axis passing through the center of the payload. Turning could take place more rapidly than simple forward motion since the stability problems associated with having a forward bag on each hub simultaneously inflating were not encountered. During turning a rear bag on one hub and a forward bag on the other could be simultaneously inflated without producing stability difficulties. (Here and throughout this discussion "forward" simply refers to sectors located towards the, arbitrarily chosen though consistently used, "front" side of the vehicle.) In this way each hub could be rotated without concern for the inflation state of the other hub. A test of turning using only one hub to execute the turn showed that this did not work well due to the twisting suffered by the stationary hub.

5.5 Slope-Climbing Abilities

The slope-climbing capabilities of the Phase II prototype fell well below those of Phase I. This section discusses the test results and details the design changes responsible for the differences.

The Phase II prototype was tested on grassy slopes of 6 and 15 degrees, and a cement staircase of 25 degrees. Only the 6 degree slope could be climbed with any confidence. Several tests showed that "1-2 mode" would not work on this shallow grade, but "2-3 gap" mode performed satisfactorily. Numerous tests were performed on the 15 degree slope, with inconclusive results. The vehicle made virtually no progress on the 25 degree slope. The slope limit of the Phase II vehicle therefore lies between 6 and 15 degrees. The reasons for this low value are outlined below.

The 15 degree slope provided the most information on slope-climbing problems. As illustrated in Figure 5.3, the Mars Ball failed to climb this slope because the "critical sector" (marked **CS**) was pinched underneath the hub. The critical sector is defined as the most downhill deflated sector; the uphill progress depends entirely on the successful inflation of this sector. Unfortunately, the act of rolling

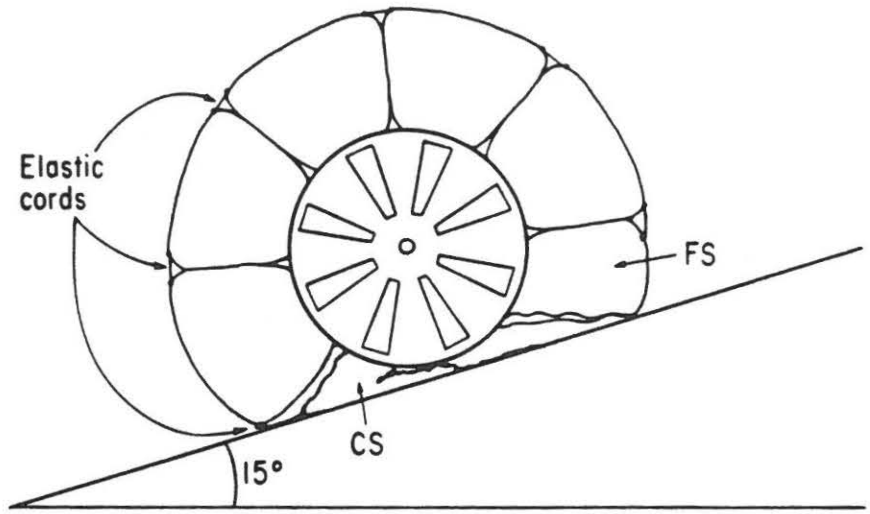

Figure 5.3. Limitation to slope-climbing by the Phase II Mars Ball. When negotiating slopes the critical sector, **CS**, could become pinched beneath the hub, preventing further progress. **FS** refers to the front sector.

tended to wrap the forward deflating sectors around the hub in the uphill direction. When the time came for such a sector to inflate, it was usually bunched up forwards and uphill of its desired position. When inflated, the critical sector would lift the vehicle and eventually tip it back downhill. The elastic cords connecting the sectors (marked **E** in Figure 5.4) were intended to counteract the forward-wrapping tendency, but the elastic was not strong enough to pull the trapped sectors from underneath the rims of the heavy hubs. We attempted one inelegant solution to the trapped sector problem: raising the hub off the trapped sector by slightly inflating the forward sector marked **FS** in Figure 5.3. This did allow elastic cords to position the trapped sector correctly, but the inflation of sector **FS** applied a downhill force which negated all uphill progress.

We attempted several other means of better sector positioning without inflation of uphill sectors, but none worked satisfactorily. Figure 5.4 shows several ways in which elastic cords were attached to the sectors. These cords were intended to pull the sector towards the hub during deflation, and therefore avoid the tendency

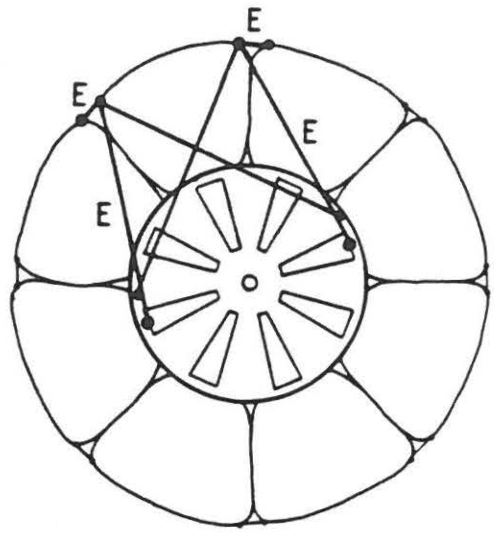

Figure 5.4. Several of the configurations of elastic cords, **E**, used to allign sectors.

of the sectors to wrap around the hub in the uphill direction. While these rigging schemes did provide slightly better alignment, the sectors still tended to be trapped under the hub forward of their ideal position.

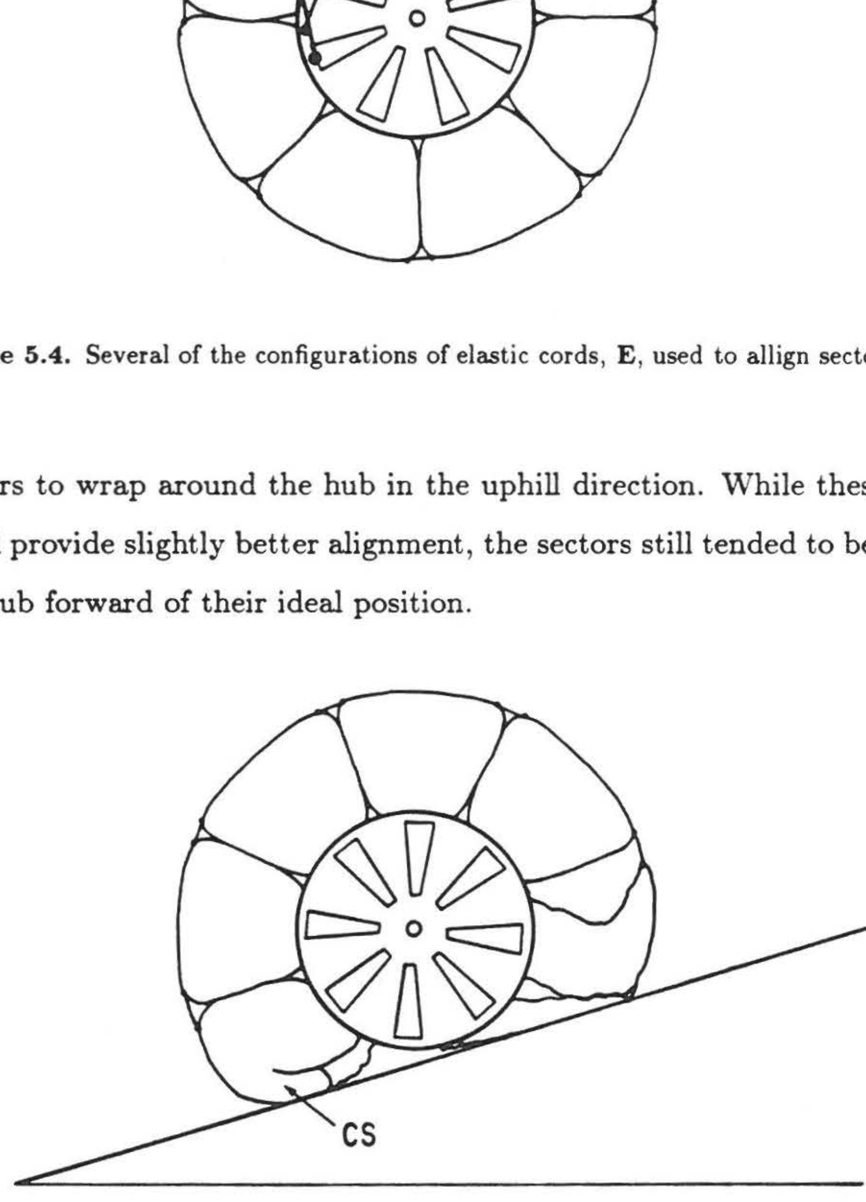

Figure 5.5. A second limitation to slope-climbing by the Phase II vehicle. The distorted critical sector, **CS**, did not push the hub uphill.

Figure 5.5 illustrates another difficulty in the climbing procedure. The deflated critical sector was positioned in a marginally adequate way, but inflation led to the distorted sector shape shown in the figure. Internal pressure in the sector and tension in the fabric acted to straighten out the sector; ideally the sector footprint would remain fixed to the ground and the hub would be pushed uphill. Instead, the hub remained almost stationary and the footprint slipped against the grassy slope in a jerky fashion. In the end, the sector extended backwards in almost exactly the position the previous sector held. The uphill progress was minimal.

This problem may in part be attributed to the slipperiness of the grass slope and the slickness of the nylon sector material. The friction between the hub and the surface was substantially more than the friction between the sector footprint and the surface. If, in Figure 5.5, the hub could slide freely against the surface, the buckled sector might have pushed the Mars Ball uphill. A rough tread on the sector end might have substantially improved the climbing abilities. Conversely, a tread might have left the sector buckled as in Figure 5.5, but would not have lifted the vehicle uphill.

The sector shape and internal pressure may also have been contributing factors to the slope-climbing problem. The long, narrow aspect of the sector wall causes the sector to be highly susceptible to folding. If the sector had been shorter, the more circular sector shape may have better resisted deformation. A higher internal pressure would also have prevented the buckling; in Figure 5.5 the buckled sector would have been able to lift the vehicle without sliding. Equivalently, a lighter vehicle would have been easier to lift with the same internal pressure. Neither the sector shape, internal pressure or vehicle weight could be easily altered, so these conclusions could not be tested.

The sector buckling may be caused in part by the hub design. The base of the sector was virtually in contact with the ground. Therefore, the sector began to carry the load of the vehicle immediately upon inflation. The footprint location is thereby fixed at the moment of inflation. In the Phase I prototype, the sector base was recessed from the hub rim, allowing the initial stages of inflation act to align the sector in the proper orientation; the footprint was therefore better placed when the inflating sector started to bear the weight of the vehicle.

The fact that Phase I prototype had considerably better slope-climbing abilities merits analysis. It differed from the Phase II design in almost all the categories discussed above, so it is difficult to pinpoint the precise reason for its success. First of all, the sector base was well recessed from the hub rim. Secondly, the ratio of sector length to hub radius was about 1:1, half that of the Phase II prototype. Third, the ratio of internal pressure to vehicle weight was substantially more favorable. Fourth, its outer felt tread provided much better traction against the slope. Finally, the sectors were strongly interconnected by the outer plastic sheath.

Figure 5.6 shows the effectiveness of sector interconnection and recessed hubs in aiding climbing. Interconnecting sectors on the Phase I prototype, on the left, pull the critical sector backwards. The recessed hub allows the critical sector to be positioned immediately adjacent to the downhill inflated sector. When inflation begins, then, the rearmost part of the critical sector is first to fill. During inflation, the vehicle rolls forwards almost like a paddlewheel. The Phase II prototype, on the right, operates in a very different manner. The critical sector is pinched directly below the hub, with none of its volume extending to the rearmost part of the open volume. During inflation, the force of inflation is directed up against the hub. This action lifts the hub, and eventually the hub falls forward. The wheel acts more like a set of radial pistons in this case. For uphill rolling, the "paddle wheel" motion proved significantly better than the "piston" motion. The opposite tends to be true for obstacle climbing, as discussed in the next section.

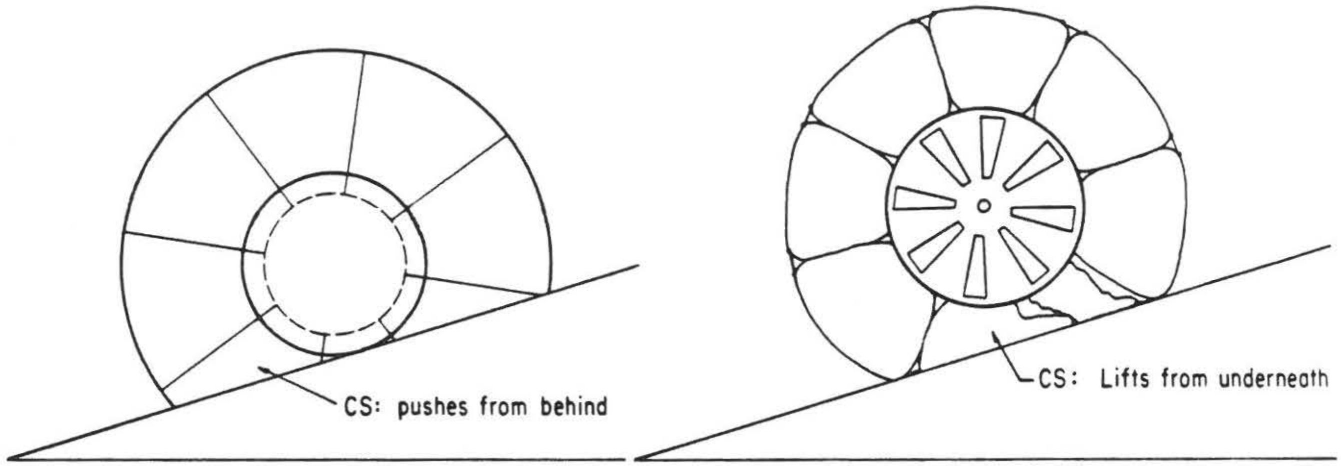

Figure 5.6. Comparison of manners of slope-climbing by the Phase I (left) and Phase II (right) vehicles. The critical sector, **CS**, in the Phase II prototype was frequently trapped beneath the hub, and inflation tended to lift the vehicle until it fell forward. The Phase I critical sector was better positioned to roll the wheel uphill by pushing from behind.

5.6 Obstacles

Experience with the Mars Ball demonstrated that obstacles (defined here as any deviation from smooth ground) could be broadly divided into two classes: those smaller and those larger in areal extent than the footprint of a single inflated bag (approximately 1 m^2). Small obstacles can be thought of as providing surface roughness while larger obstacles represent impediments that must be surmounted by the vehicle. Hence the performance of the vehicle is evaluated separately for each obstacle scale.

The small obstacle performance of the Mars Ball was excellent. When encountering isolated small obstacles (less than about 30 cm in height) the sector contacting the obstacle would simply deform around it. Thus obstacles at this scale did not significantly impede or slow the progress of the vehicle. No testing, however, was attempted over rough surfaces such as a rubble-strewn field. We expect that as long as the scale of the roughness remains in the "small" range discussed above, the behavior of the Mars Ball should not differ from that seen in the tests over smooth ground.

The success of the Mars Ball when encountering larger obstacles depended primarily on the height of the obstacle. The largest obstacle the vehicle could consistently surmount was a box 0.6 m tall by 0.7 m wide (in the direction of travel). Two of these boxes placed side by side (producing an obstacle 1.4 m wide) were also successfully negotiated. The Mars Ball could not traverse taller obstacles. (In all cases the large obstacles were features of positive relief placed in front of one of the wheels and were at least as long as a sector width.) To provide an explanation of this behavior a detailed discussion of the vehicle's operation at obstacles is required.

The critical factor in determining whether or not the Mars Ball can climb over a given large obstacle is the configuration of the bags when the vehicle first begins to climb over the obstruction. Normally the Mars Ball begins negotiating obstacles by performing the standard rolling process until forward bags fall atop the obstacle instead of on the ground (see sequence in Figure 5.7). The forward bags atop the obstacle are then deflated and the remaining rear bags inflated until the forward most bag behind the obstacle is inflated. If the obstacle is too tall the vehicle has no chance to roll so that some bags are over the obstruction. In this case the vehicle cannot climb forward since the obstacle is essentially a wall. This absolute maximum limiting height is approximately the height of the hub above the ground (roughly 1.3 m in the current design).

The configuration of the vehicle at this point determines whether it can roll over obstacles shorter than this limit. Specifically it is the trailing deflated sector atop the obstacle that decides the success of the climb (sector **C** in Figure 5.8f). Normally, to move forward this deflated bag would be inflated, thus pushing the Mars Ball onto the obstacle. On obstacles larger than about 0.6 m, however, inflation of this sector would often push the vehicle backwards, off the obstacle. This is because the center of mass of the vehicle was not forward of the inflating bag

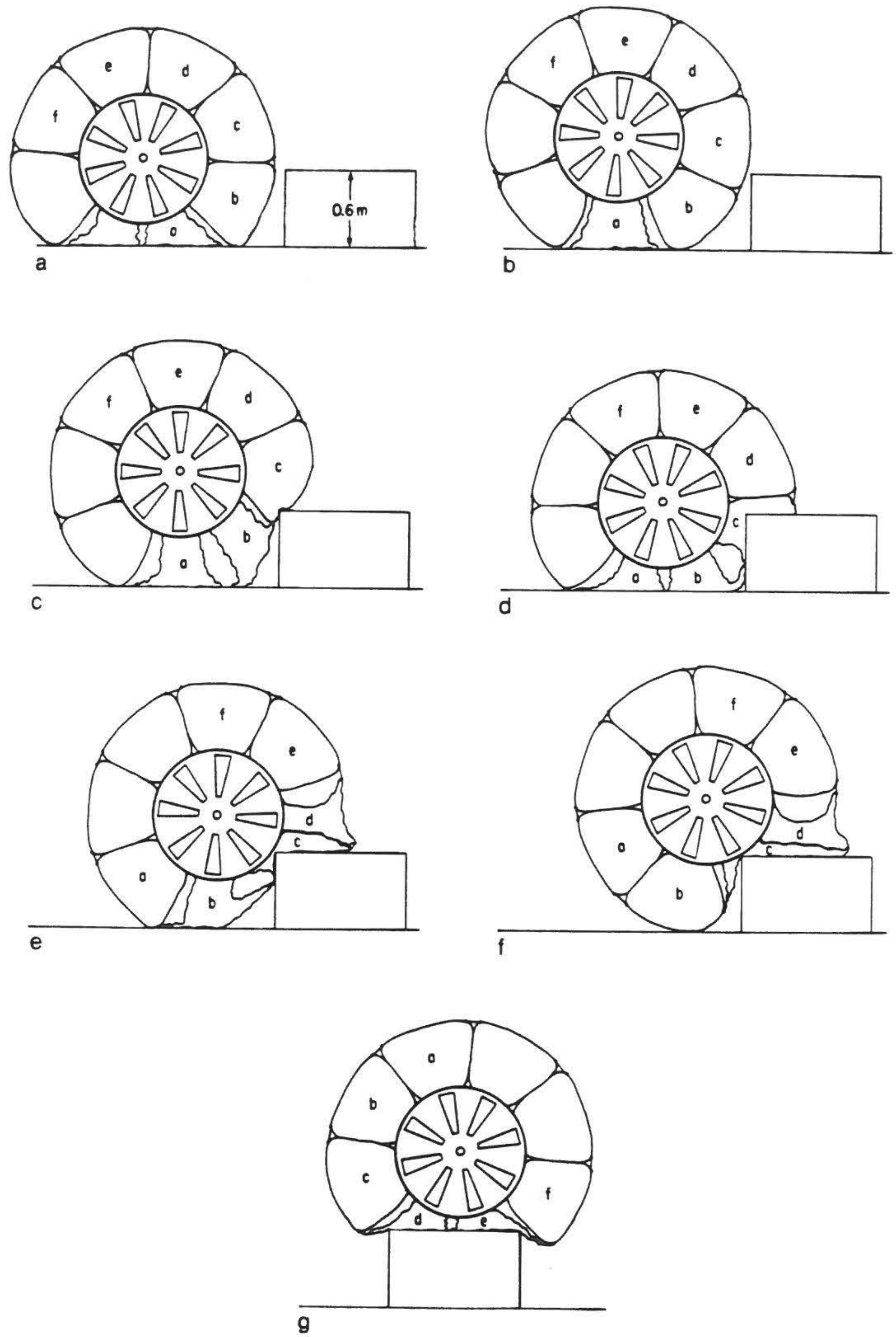

Figure 5.7. Mars Ball obstacle-climbing sequence.

due to the presence of the obstacle. In other words deflated bags that should have been behind the vehicle were "wound up" over the top of the obstacle and could not fall back to their correct positions. This difficulty was sometimes encountered on objects smaller than 0.6 m as well. In those cases the obstacle could usually be surmounted by backing the vehicle up and trying several times. Eventually the exact placement of the bag over the obstacle step would be such that the vehicle could climb over the object. This problem was usually seen at obstacle sizes close to the maximum height limit.

Several attempts were made to improve the obstacle capabilities of the Mars Ball. Most of the experiments were aimed at pulling the deflated sector atop the obstacle back off so that inflating it would push the ball forward. The most successful solution was the attachment of surgical tubing between corners of adjacent sectors. The elastic would sometimes help pull the bag into position. Often, however, this "critical sector" would be pinched between the hub and the obstacle allowing no opportunity for correct placement. Experience with the problem revealed that the true upper limit for obstacles was 0.6 m or roughly half the sector length.

Other characteristics of the vehicle's obstacle climbing ability should also be noted. When climbing over objects, the center of mass of the particular climbing hub, as well as the vehicle as a whole, is not raised the full height of the obstacle. Instead much of the obstacle height is absorbed in the deformed sectors. In fact once the Mars Ball was atop an obstacle it basically rolled on the hub across the obstacle in the "2-3" rolling mode. Thus less energy is expended in lifting the Mars Ball than if the whole vehicle were raised by the height of the obstacle. A final observation is that the width of the obstacle was not important. Once the vehicle was over the initial obstacle step no further difficulties were encountered, regardless of the remaining obstacle size.

Although the Mars Ball was never tested over "negative" obstacles, such as a trench, we expect the performance to be similar to "positive" obstacles. The limiting difficulty (assuming a symmetric trench) would be the positive step at the far side of such an obstacle instead of the first step at the nearside. Thus we expect the deepest trench the Mars Ball could roll past would be 0.6 m deep.

5.7 System Efficiency and Power Consumption

This section discusses the limitations of the Phase II vehicle, and how these limitations affected the achieved speed and power consumption of the vehicle. Since the goal of our project was to determine the maneuvering abilities of the design, neither the speed nor the power consumption of the test vehicle were optimized. As discussed in Section 5.3, the Mars Ball rolled at an approximate speed of 1 meter per minute while consuming 1600 watts of power. The slow speed and high power consumption are both due to engineering flaws not intrinsic to the Mars Ball concept.

The power consumption played virtually no role in determining the maximum speed of the vehicle. The dominant factor was the long deflation time of the sectors. The sectors were vented directly to the atmosphere to deflate ("passive deflation"), so that only the overpressure within a sector acts to force air out. The overpressure is large when the sector is full and carrying the vehicle load, but becomes vanishingly small as the sector empties and the load is carried by adjacent sectors. This slow sequence required from 45 seconds to 1 minute per sector. The sluggish deflation may be partly due to the narrowness of the duct work connecting the sectors to the blowers and atmosphere. This question is discussed further in Section 6.3.2.

Appendix A discusses the power consumption of the current system versus theoretical calculations, with the basic result that the overall system efficiency is probably on the order of 4%. It is easy to imagine that leaks in the system, losses in the blower motors, etc., explain the remaining inefficiencies.

5.8 Automatic Computer Control

We implemented a low level of automatic computer control which functioned well. The computer algorithm for rolling on flat terrain followed the sequence described in Section 5.3. The control program used only the wheel orientation sensors to make decisions on the timing of inflations and deflations. The automatic rolling proceeded almost as fast as the manual mode. The computer code allowed the vehicle to roll in "1-2 gap" mode or "2-3 gap" mode; both worked satisfactorily although the "1-2 gap" mode proved most efficient. The "2-3 gap" mode succeeded several times in negotiating 0.6 m obstacles, but this was partly fortuitous. The code was not designed to switch between "1-2" mode and "2-3" mode, as would be required to roll along level terrain and then climb an obstacle or slope. Such a capability would be fairly easy to implement using a timer which determined when forward progress had stopped and a change in the rolling algorithm was needed.

5.9 Summary

The testing of the Phase II vehicle pointed out many inherent strengths and weaknesses in the design and construction of the test vehicle. The tests demonstrated that the fundamental principle behind the Mars Ball is sound: the vehicle successfully and stably rolled over level ground, obstacles, and modest slopes. An advanced version, carefully designed to take full advantage of the lessons learned in this testing, should provide significantly improved performance. Issues of bag shape and placement and vehicle stability will require careful attention in future Mars Ball implementations.

6. RECOMMENDED DESIGN CHANGES

6.1 Structure

The materials used in our prototype vehicle endured fairly well during the extensive test period. The materials, however, are generally not sufficiently durable for long periods of use, and many are excessively heavy. Additionally the structural design places loads at various locations on the vehicle that might eventually lead to permanent deformation with extended use. Clearly an advanced prototype or actual Mars-worthy vehicle would have to make extensive use of improved materials and structural design. Also other structural issues, such as compactness and self-deployment on the Martian surface, must be addressed in an advanced design. This section discusses these issues and suggests possible remedies for some of the problems.

Any vehicle, regardless of the materials incorporated in it, must withstand the repetitive loads to which it will be subjected. On the Mars Ball there are four loads of special importance.

6.1.1 Hub "Breathing"

As compressed air is cycled between bags, the pressure in the hubs changes slightly. Also, as the blowers are turned on and off between periods of activity, the internal pressure alternates between atmospheric and high pressure. This continued breathing stresses the side walls of each hub. On the Mars Ball this was evident in paint cracks at strain locations. A vehicle intended for continuous use would have to withstand this breathing without failure. This difficulty is often faced by terrestrial equipment (*e.g.*, compressed air tanks) and should be easily resolved.

6.1.2 Shutdowns

It is envisioned that each time the Mars Ball takes a soil sample, waits out the night, endures a dust storm, or deposits equipment on the ground, it will deflate the lower sectors and set itself down on the ground. These repetitive cycles will also take their toll on the Ball.

Hub edges: Setting down on a rocky or rough surface might damage the hubs or result in some sliding. A thick (perhaps pliable) rim is important. This situation also is potentially dangerous for bags which might be pinched between rocks and the hub. Since the prototype Mars Ball has only operated on grass and smooth concrete to date it has not been necessary to fully address this problem on the current prototype (which, nevertheless, has carpet-covered foam-padded rims).

Payload and Axle bending: Every time the ball sets down the payload flexes. In the current design this is because the weight of the vehicle shifts from the hubs to the payload. The payload again flexes as the vehicle rises up off the ground. Since occasional payload-ground contact will probably be necessary on a larger vehicle as well, the payload will continue to be stressed. On the current vehicle a heavy, strong payload bears the load well. Lighter weight assemblies would have to be sufficiently durable to withstand this stress. Also, during every revolution of the axle the flex due to the suspended payload travels through 360 degrees. An axle must bear this continuous stress.

A related matter is the scaling of the mass distribution on a Mars-worthy vehicle. Currently the hubs are very weight inefficient. A design which utilized lightweight hubs and a fully loaded payload would change the payload/hub mass ratio. The effect of this change on the dynamics of the vehicle would have to be investigated.

6.2 Wheel Bags/Sectors

Several modifications to the existing sector design will be required for a Mars-worthy vehicle. These include:

6.2.1 Bag Material

The harsh environment and rough terrain of Mars will require extremely durable tire sectors. In particular, the fabric chosen for the inflatable tire sectors must remain flexible at the low Martian surface temperatures, be puncture resistant, and be resistant to ultraviolet radiation and an oxidizing atmosphere with H_2O, H_2O_2, and HO_2. One study [11] indicates that the tenuous nature of the atmosphere leaves it only mildly oxidizing by Earth standards; and that materials long lived against oxidation on Earth will also be durable on Mars. Such materials are now under study due to the Soviet Union's decision to complete a mission to Mars with sample return.

6.2.2 Bag Design

More reliable operation might be expected from bags of a double-skinned construction. An outer treaded layer could provide enhanced slope-climbing performance and additional resistance to abrasion. The inner layer should be optimized for gas retention and incorporate a self-healing mechanism.

6.2.3 Sector design

Three main issues associated with the general design of the sectors have been addressed in earlier discussions (Chapters 3 and 4) and are summarized below.

Number of Sectors: The effectiveness of climbing and obstacle engulfing is related to the number of sectors. The more sectors, the more effectively the Mars Ball climbs hills, rocky slopes and passes over bouldered terrain. In testing the abilities of both the Phase I and Phase II vehicles, the limiting situation frequently occurs when the "critical sector" (to be inflated next in order to advance over an obstacle or up a slope) is positioned too far forward, rolling the wheel backwards during inflation. Dividing the sector into several segments which could be inflated sequentially would ameliorate the problem and should improve performance both in slope-climbing and in negotiating obstacles. Limits will be reached beyond which both the cross-sectional shape of the bags and the number of valves and switches on the vehicle will become unwieldy; we suggest that the number of active sectors should be increased, probably to 16.

Redundancy in bag sectors with available bags is also essential. One can expect some degree of degradation of even durable materials due to the sharp edges of lava flows and the points and edges of rocks which weather without the smoothing effect of flowing water. Temperature extremes and especially low temperatures will tend to make most material brittle and susceptible to cracking and puncture. Thus the vehicle must be able to operate with some disabled sectors, although some performance reduction should be acceptable.

Sector Length: Although the overall size of the Mars Ball can be increased by lengthening the sectors in relation to the hub radius without penalty in launch size, our experiments have shown that poor lateral stability and tendencies for deflated sectors to fall out of alignment result from sector-length / hub-radius ratios greater than about 2:1. Larger ratios may be permissable if used with some mechanism to confine the inflated bags (next section).

Interconnection of Sectors: The Phase I vehicle successfully climbed slopes of up to 24 degrees in part because of its envelope-tread design and recessed hub which constrained the initial inflation of the critical sector to the rear of the wheel's center of gravity. However, this same feature proved to be a disadvantage in rolling over obstacles. An efficient means of linking adjacent sectors together while still allowing each to function independently remains to be devised. Finally, a method of stowing the retracted sectors will be required for the voyage to Mars.

6.2.4 Sector-Hub Interface

The way in which the sectors connect to the hub contributes to both vehicle stability and slope-climbing capability. As discussed in Section 5.1, shortening the bags of the Phase II vehicle improved stability, partly due to the resulting overhang of the sectors onto the hub. The bag shortening produced not only a change in length but also a change in shape of the bags. The new sectors were fatter and more rounded where they connected with the hub. With this new shape, the sectors were laterally constrained by the hub rims. The significant improvement in stability that resulted from this change suggests that this feature should be exploited in a Mars-worthy vehicle. Furthermore, if the hub base is recessed from the hub rim (as shown in Figure 5.6), then the sector may begin to inflate before it bears the weight of the vehicle. This could improve the rolling and climbing abilities of the vehicle, as outlined in Section 5.4. A recessed hub with rounded sectors at the hub-sector interface is therefore recommended.

6.2.5 Optimum Pressure Differential

The pressure differential used in the current prototype is clearly adequate to support the weight of the vehicle, but we are near the limit of stability problems. Our experiments have demonstrated that the sector rigidity is crucial to the lateral stability of the vehicle, and that a higher pressure-to-weight ratio (and therefore smaller footprint) is highly desirable. It appears, then, that pressure differential and footprint area may not be freely interchanged without affecting vehicle performance. We have not determined an analytic expression for the dependence of lateral stability on pressure differential, but we conclude that a higher differential (or lower mass) would improve the overall performance of the Mars Ball. Appendix A discusses the cost of such a change in terms of power consumption.

6.3 Air-Flow System

The current Mars Ball system for inflating and deflating sectors was chosen on the basis of the availability and ease of fabrication of materials and other components. No attempt was made to maximize efficiency or to build for Martian survivability. Rather, the design criteria were overall simplicity of both vehicle construction and control. The current design is more fully described in Section 4.2.

6.3.1 Gas Recirculation

Perhaps the single biggest improvement in overall efficiency, speed of operation and protection from dust can be obtained by simple reuse of compressed gas, also called active deflation. Currently, the compressed atmosphere is stored in the central hub. Each sector is then inflated individually from this reservoir. When the sector is next deflated, its load of compressed air, which represents power consumed by the vehicle, is simply vented back to the atmosphere. The process of venting the sectors to achieve deflation is also the slowest process in the sequence of moving the Mars Ball, and would be speeded by active deflation.

Recirculation can be achieved by supplying an additional airflow path between the exhaust port of the various sector valves and the inlet port of the compressor or blower. A single additional valve at the compressor inlet would be required to control whether the compressor is drawing air from the atmosphere or a deflating sector. It may be useful to have two plenums, at maximum and minimum pressure.

Since the sectors are constructed of a necessarily pliable material, there will be a tendency for this material to cover and seal the outlet port within the sector, as was found to be the case even with the current passive deflation. Blockage of the port was easily prevented in passive deflation by, in effect, constructing a small fluted cage around the exit. We anticipate that active deflation will require a redesign of this cage to prevent total blockage of the port.

6.3.2 Piping

The choice of tubing material and size can contribute to the speed and efficiency of the design. The inside diameter of all conduits carrying airflow should be as large as possible to reduce frictional and viscous losses. Wall thickness and weight should be kept to a minimum. The low operating pressures of the vehicle place no great strength requirements on the pipes but for a vehicle employing active deflation of sectors, the tubing must be able to withstand negative as well as positive pressures without collapsing or bursting. The current test bed employs 2 inch ID PVC piping due largely to the ready availability of such tubing and fittings.

The limiting factor on the speed of the current vehicle is the time to deflate a sector, which presently is longer than the inflation time. The only factors in the deflation time are the pressure differential and pipe and orifice drag. These go approximately as $1/area$; so that doubling the pipe diameter should reduce the required time by a factor of four. The exact relationship depends on the nature of the pipe, but should be between $(area)^{-1}$ and $(area)^{-5/4}$. The pressure differential on Mars will be smaller ($\leq \frac{1}{3}$ Earth prototype); but the flow rate only depends on $\sqrt{\Delta P}$, so that the intrinsic flow rate is expected to be approximately $\frac{1}{2}$ that of the Earth-based prototype.

The pipe and orifice sizes must therefore be increased on a Mars-going vehicle, but a factor of 2 increase in diameter would increase the current prototype's speed significantly, even on Mars. This increase could also shorten the inflation time, which would have a smaller, but noticeable effect. The dependance of the inflation time on pipe size is not as clear, as it also depends on the characteristics of the compressor. The outlet of the centrifugal blowers used on the current vehicle is approximately the same size as the piping, so we don't expect a large gain. It should also be noted that pipe drag is a frictional loss, tantamount to power required to move the vehicle, and thus should be minimized.

All piping and valves should be housed within the hubs to as great a degree as possible. The current design with the individual sector valves mounted on the exterior of the hubs was adopted to allow access to the valves for repair and adjustment. Internalizing the plumbing would also greatly decrease the number of openings that must be sealed between the hub and the ambient Martian conditions.

6.3.3 Self Protection

One of the more obvious hazards to a vehicle which uses near-surface Martian atmosphere as an integral part of its propulsion mechanism is the problem of dust. The introduction of significant numbers of particles into the compressor must result in the deterioration of its efficiency. This deterioration might be rapid enough to cause failure of the Mars Ball, depending on the size, flux and hardness of the particles. If the particles accumulated in the hubs and sectors they would also be expected to degrade the performance of the vehicle as a whole.

Filters will probably need to be an integral part of the air intake system. These filters must have a pore size which is smaller than both the majority of Martian dust and the smallest grain which can cause damage to the compressor. However, with decreasing pore size the cross sectional area of the filter must increase to maintain the efficiency with which air can be moved through the system under the pressure differential available from the compressor. Of course a method of clearing the filters would then be required.

The large scale dust storms to which Mars is subject would necessarily halt the Mars Ball. In order to survive these storms and continue operations afterwards, the vehicle must have the capability to completely close off its interior. As noted above, all valves and piping should be internalized to limit the area which needs to be sealed. This should leave the airflow system with only a single inlet and outlet port on each wheel. Each of these ports would then be fitted with sealable end caps which could be closed off under either Earth based or internal computer control.

The current prototypes use valves which are either inflating or deflating the sectors; for self-protection and for maximum flexibility it may be desirable to have a third state in which the sectors can be sealed off at any level of inflation.

6.4 Control System

Due to the simplicity of the design, the Mars Ball control system need not be significantly more complex than our current implementation. Mission control will transmit high-level commands, such as "rotate 30 degrees south, travel 200 meters, then turn 45 degrees north and stop". Such commands will be decoded by the on-board computers and acted out under internal control. An inertial guidance system coupled with an imaging system will periodically inform mission control of the rover's progress.

Several simple sensors will be required to inform the rover of the terrain. Hazard sensors, such as laser-ranging devices must report the location of very large boulders, precipitous drop-offs, and steep canyon walls. The Mars Ball will be equipped with sensors to measure the tilt of the vehicle with respect to the surface, both side-to-side and front-to-back. The vehicle will respond to the terrain by selecting the optimum algorithm from its repertoire of strategies, changing as necessary until the destination is reached. Position encoders, such as those already in use on the prototype, will test the success or failure of the command sequences. If the position encoders and/or the inertial guidance system indicate that the vehicle is not rolling forward, the control program will assume that the slope has changed or a small obstacle is underfoot. The control program responds by switching to the next higher level of obstacle and slope climbing strategy. If, after several attempts, forward progress proves impossible, the control software will direct the vehicle to back up and skirt the difficult region. In particularly difficult circumstances, specific instructions from the ground-based controllers may be required.

In order to assess forward progress, the Mars Ball will require an inertial guidance system such as gyroscope-stabilized accelerometers. For example, on sandy dunes or crumbling slopes, it is possible that the wheels could turn indefinitely without producing uphill motion. The accelerometers would report this to the control program, and the climbing algorithm or direction of motion would be changed. Thus the on-board intelligence of the Mars Ball itself need never analyse obstacles in detail, for example through stereoscopic imaging. As long as the hazard sensors reveal no immediate danger, the vehicle either rolls over obstacles, or gives up on them and tries a different route. This is fundamentally the same strategy employed by many children's toys, and would not be difficult to implement in the Mars Ball.

Some additional circuitry will be required to monitor the status of the vehicle. Pressure sensors will report on the output of the compressors and alert the control system of any leaks. Some circuits should be redundantly protected, and the option of full manual control from Earth should be preserved.

6.5 Power Supply

Energy efficiency was not considered vital in the construction of the prototype, but is clearly of the utmost priority on Mars. Appendix A describes in full the current and predicted energy budgets, and the salient points are repeated here. The current prototype weighs 500 kg, travels at about 1 meter per minute, and consumes 1600 watts continuously. We calculate the efficiency of the current system is about 4%. Using reasonable assumptions, we predict that a similar Mars Ball of the same mass, under Martian gravity and atmospheric pressure, would travel at 2 m/minute and consume 180 watts when rolling exclusive of payload and guidance system power requirements. This value is strongly dependent on the anticipated compressor efficiency; we have used a conservative value of 20%. Vehicle mass carries a heavy premium: reducing the mass to 250 kg cuts the power consumption to 60 watts. The use of storage batteries, charged when the vehicle is not rolling, may reduce the peak load.

As presently operated the blowers run continuously. When pressure within the central hub reaches the operating pressure of 50 mbar, a relief valve opens and vents the additional pressurized gas to the atmosphere. Clearly there is no need for the compressor to be drawing power when the machine already has a full complement of compressed gas and is not moving. The compressor should therefore be under computer control, being engaged only to pressurize the hub or when the wheel is in motion. The computers are already in control of the valves, and should be able to accommodate the additional control without difficulty.

In addition to the efficiency with which the compressor can convert electrical power to pressurized volume, other considerations include the susceptibility of the unit to degradation by the environment and the size and weight of the unit. Certainly each wheel should be equipped with redundant compressor units.

Power requirements in the range of 180 watts could be supplied by solar cells. An array measuring 2 to 5 square meters (depending upon compressor efficiency), mounted above the payload and tiltable towards the sun, would be sufficient. The array size obviously scales with the power required, which in turn depends on the vehicle weight, as discussed in Appendix A.

6.6 General

In addition to withstanding the stresses resulting from vehicle motion and shutdowns, the materials on a flight-worthy Mars Ball must meet certain other requirements. They must be light, strong, and durable. Temperature variations, dust storms, and radiation hazards must be weathered. There is a great deal of space flight expertise which must be applied to this particular mobile lander.

The overall size of a Mars-worthy Ball must be large. Since most of the Mars

Ball's volume is inflatable, it may be possible to change the size of the vehicle without greatly affecting the mass. A larger wheel radius would obviously prove helpful in climbing over rocks or viewing distant terrain. Appendix A gives rough calculations of the effect on power consumption of scaling up the size of the vehicle, and concludes that a larger vehicle could be more energy efficient as long as the vehicle mass does not appreciably increase. Given the lessons of our experiments, however, this conclusion should be tested empirically to determine what other properties of the vehicle depend on size.

Finally the package must fit into a launch vehicle and probably an aeroshell for delivery to the surface. Hence it will be desirable to pack the vehicle into as small a volume as possible. With the bags deflated the Mars Ball is still somewhat space-inefficient. With the exception of the payload the volume surrounding the axle is not used. Perhaps the axle can be telescopic, extending to full length during the first few rolls of the Ball. This reduces shipping size, but introduces additional failure modes and strength requirements. The non-vehicle volume could also be packed with other instruments. Other possibilities must be considered.

Despite these, and probably other undiscovered difficulties, the problems surrounding the construction of a large scale, Mars-worthy vehicle of this design are not insurmountable. Preliminary calculations suggest that a full scale, solar powered, Martian Mars Ball could have a mass of approximately 500 kg. A rugged, lightweight structure would be an important aspect of such a vehicle.

7. SUMMARY AND CONCLUSIONS

The Mars Ball Project was an initiative by a group of graduate students at the Lunar and Planetary Laboratory of the University of Arizona. The objective of the project was to test an intriguing concept for a semi-autonomous roving vehicle. Ideas for such vehicles are numerous; many can be generated by simple brain-storming sessions. However the gap between first concept and final operating machine is large. Determining whether a given proposal has merit can range from quick "back of the envelope" calculations to full-scale design and engineering projects costing millions of dollars and lasting many years. Obviously the former is insufficient to fully justify building a given rover while the latter precludes examining all of the possible candidates. The Mars Ball Project studied one proposal at an intermediate level, actually building a working model of a rover in order to determine whether or not it would work in the real world, how well it might perform, and what hidden problems might need to be solved in a full-up engineering study.

The history of the project, as detailed in the preceeding chapters, is one of proceeding from first concept through various test beds, examining along the way the capabilities and faults of the various parts of the whole. The ultimate goal was to produce a vehicle which was able to meet the criteria set out for a Martian rover by NASA under controlled conditions here on Earth. The final configuration was generally successful in all the requirements placed on it while deficient in some aspects. Most of the deficiencies can be traced directly or indirectly to the limits of the scope of the study; the time, money and personnel available were not adequate to the final task of determining the feasibility or applicability of the design. We have, however, demonstrated that such a low-tech vehicle is capable of operating over the sorts of terrain visible at the Viking lander sites with a minimum amount of direction from a human operator. Thus the concept has passed its first test and has proven capable of performing the tasks envisioned for a Martian rover.

Briefly, the vehicle as presently constructed can travel at a speed of approximately 1 meter per minute, ignore most small rocks and boulders, surmount larger boulders up to 0.6 m tall with simple changes in its motion algorithm, and climb moderate slopes.

The Mars Ball accomplishes this without relying upon complex, expensive or heavy hardware. As has been demonstrated, such a vehicle can be built using only very simple technology. Since the bulk of its operating size is made up of gas drawn from the atmosphere and its "motor" can be any small device for moving that air, the size and weight of the portion of the vehicle devoted to motion can be minimized, saving a large measure of any launch weight for the scientific payload. Its compactable design and low weight offer the possibility of sending a number of rovers to different sites on Mars with a single interplanetary mission.

The general design of the vehicle offers several unique advantages. The free-swinging central payload reduces the chances that the vehicle will be stopped by an obstruction encountered between the wheels. Simple deflation of the wheels places the payload in firm contact with the ground for seismic studies, core drilling and other experiments. Finally, the width of the Mars Ball and its large tire size minimize the possibility of the rover suffering catastrophic upset.

Final determination of the suitability of such an approach to Martian mobility rests on the availability of materials and components which can perform under Martian conditions. Questions which still need to be answered include: Is there a material for the inflatable sectors which can maintain flexibility at the low temperatures of Mars, survive in the face of the surface UV flux, and resist tears and punctures over the expected operating lifetime of the mission? Is there some combination of compressor type (be it piston, impellor or turbine) and filtration system which will keep the vehicle from choking on the Martian dust? What is the optimum number, shape and arrangement of sectors, and how should they be interconnected? What are the actual power requirements of the final vehicle and can such requirements be met with solar cells and storage batteries?

These and other engineering questions were beyond the scope of this project. However the Mars Ball approach to mobility, namely a large, two-wheeled, inflatable sector-driven vehicle, has demonstrated enough potential to warrant a design study in greater depth.

APPENDIX A: Power Consumption Calculations

The following appendix descibes the derivation of the theoretical power consumption values for the existing prototype and a hypothetical Mars-going version. The results indicate that the Mars Ball could be operated from several square meters of solar cells. High compressor efficiency and low vehicle mass will help the Mars Ball meet this goal.

For simplicity, we have retained the vehicle scale and mass for the Mars version. (We assume that it is possible to drastically reduce the mass of the propulsion unit through the use of appropriate materials, so that the scientific package can be included in the 500 kg figure.) Table A1 lists important parameters of the two vehicles. The primary differences are that the Mars version will travel twice as fast, use twice as many sectors, and recycle the exhausted compressed gas.

In the following discussion, we idealize the Mars Ball as two wheels, each a 2-meter radius cylinder of thickness 1 meter. The hub radius is 0.6 meters, so the inflatable volume of each wheel is of each about 11 m^3. The vehicle rests on the points of the inflated sectors. (In actuality, the points are rounded, and about 0.5 m^2 of footprint per wheel is in contact with the ground.)

Table A1: Mars Ball Design Comparison

Model	Earth Prototype	Mars Version
Gravity	9.8 m/sec^2	3.7 m/sec^2
Atmospheric Pressure	1000 mbar	6 mbar
Vehicle Mass	500 kg	500 kg
Number of Sectors	8	16
Operating Mode	1-2 gap	2-3 gap
Total Internal Pressure	1050 mbar	24 mbar
Pressure Differential	50 mbar (5%)	18 mbar (300%)
Time for Complete Revolution	720 seconds	360 seconds
Speed	1 m/minute	2 m/minute
Vertical Displacement	0.44 m	0.18 m
Pressurized Air used in 1 revolution	16 m^3	11 m^3
Gas Recycling?	NO	YES
Pump	Centrifugal Blower	Compressor

The vehicle consumes power in two ways: compressing the gas needed to propel the vehicle, and lifting the vehicle by small amounts (δz) during the inflation sequence. Due to the large Earth gravity and the limitations of our prototype, the work against gravity dominates; on Mars a better design in the lower gravity will contend primarily with the thermodynamic work of compressing the atmosphere. Other energy losses, such as radiated heat, friction, etc. are lumped into the category of system efficiency.

Our terrestrial prototype has 8 sectors and rolls most efficiently in "1-2 gap mode" described in section 2.3. The Mars design employed in these calculations has 16 sectors, and we calculate its performance in "2-3 gap mode". (Its efficiency will be higher in "1-2 gap mode", but this may only apply on the smoothest of terrains.) Since the Mars version will use 16 sectors, "2-3 gap mode" uses a smaller deflated fraction of the wheel than "1-2 gap mode" on our terrestrial prototype. As a result the Mars version moves up and down less than its terrestrial counterpart, and therefore require less energy for vertical motion and lower volume requirements for inflation and deflation.

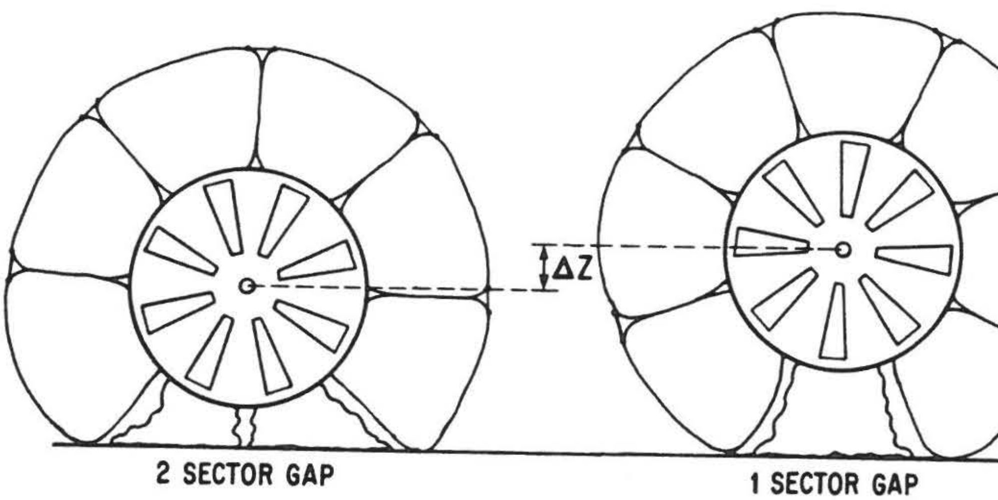

Figure A1. Work done against gravity in vertical motion of the Mars Ball.

Figure A1 illustrates the work done against gravity. When rolling on level terrain in the 1-2 gap mode, the center of mass of the vehicle moves in the vertical dimension by a distance Δz, so the resultant work $W = Mg\Delta z$. This up/down motion occurs once for every sector on the wheel, so the work done in one rotation is

$$W_{gravity} = Mg\Delta z \times N_{sectors}.$$

The resulting values are shown in Table A2. The work done on Mars is substantially less, due to the lower gravity and to the smaller vertical drop possible with a 16-sector design. The Mars value may be even lower: if inflation and deflation occur simultaneously, the center of mass need not move up or down. We retain the calculated value, though, as a conservative estimate.

Table A2

Comparison of Power Consumption on Earth and Mars

Work to Lift Vehicle (Joules)	17,200	5300
Work to Compress Gas (Joules)	1400	11,200
Total Work (Joules)	18600	16500
Total inflation time	4 minutes	6 minutes
Theoretical Power Consumption	78 Watts	46 Watts
Total Power Consumption	1600 Watts (measured)	180W/90W (predicted)
Efficiency	5% (derived)	25%/50% (assumed)

Calculations of the energy to compress the atmospheric gases are shown graphically in Figure A2. For our terrestrial prototype, we estimate that about one cubic meter of air is displaced in each inflation and deflation, for a total of 8 m^3 for one revolution per wheel, or 16 m^3 for the whole vehicle. By calculating the inflated volumes of a 16-sector wheel operating in "2-3 gap mode", we find that only 11 m^3 is required for a full revolution of the Mars version. We assume that the inflation process is isothermal. The compression will probably be adiabatic, but the excess heat will probably be radiated away. For isothermal compression, the work done by

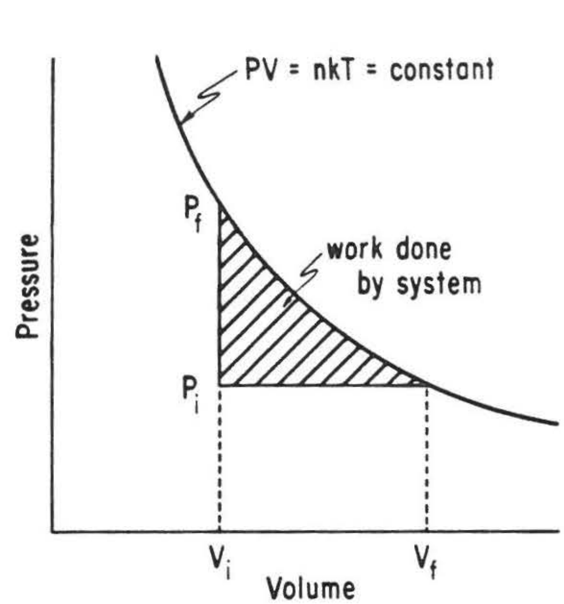

Figure A2. PdV work done during inflation of sectors.

the system is

$$W = \int_i^f \Delta P dV$$

$$= P_i V_i \ \ ln(P_f/P_i) - P_i(V_f - V_i)(\text{isothermal}).$$

On Mars, where compressed air will be recycled, we crudely estimate that this will yield an energy savings of one third. The results are tabulated below. The Mars compression work is much greater than the Earth value, due to the fact that the martian atmosphere must be compressed by a factor of four, while the Earth atmosphere need only be compressed by 5%. The energy requirements are converted to power requirements by dividing by the total inflation time for one rotation. For the terrestrial prototype, inflation occupied only about a third of the total time, so no useful work (in this idealized sense) was being done two thirds of the time. On Mars, we anticipate that the compressors will perform useful work continuously, filling either deflated sectors or the high-pressure reservoir. The inflation time for the Mars case is longer, but the time for one revolution is shorter because the very slow deflation time of our prototype will have been eliminated.

The extremely low efficiency of our terrestrial prototype is hardly surprising given the components used. In a sense, the low efficiency of our low-technology system adds credence to the belief that a well-designed compressor system should have an efficiency *well* above 5%, conceivably an order of magnitude higher.

We do not expect power output to have a limiting effect on slope climbing or obstacle negotiation. The maximum abilities in these two areas are principally determined by the geometrical properties of the design; the power output primarily determines how rapidly the vehicle will progress. In a very rough sense, we estimate the reduced speed of the rover on a slope. On moderate slopes (15 degrees), the up/down motion of the vehicle and the volume requirements would probably increase, but not by more than a factor of 1.5. (Experience from prototype I actually showed that the excess up/down motion of the vehicle was very small when rolling uphill. Volume requirement will definitely increase since the vehicle will roll lower to the ground. The maximum increase is a factor of two, i.e. the total volume of the wheel. We assume that complete deflation of every sector will not be required for rolling up a 15 degree slope.) When climbing, the hub of the vehicle is closer to the ground; we estimate that the effective radius of the wheel is about half of its maximum value. In one uphill revolution, the rover will therefore roll about 6 meters on slope, and will climb about 1.5 meters. The rover will therefore gain an additional 2600 joules of potential energy. Total energy spent in one revolution is therefore 32000 joules. Using the same efficiency estimates, we find the rover's speed will be reduced to about 30% of its level terrain speed.

The power consumption depends strongly on a number of design parameters. The most important is pressure differential, which is determined by vehicle weight and footprint area. High pressure exacts a heavy premium: doubling the pressure differential increases the power requirements by about a factor of 3. Mass is the prime determinant of pressure differential, so low vehicle mass is of utmost importance.

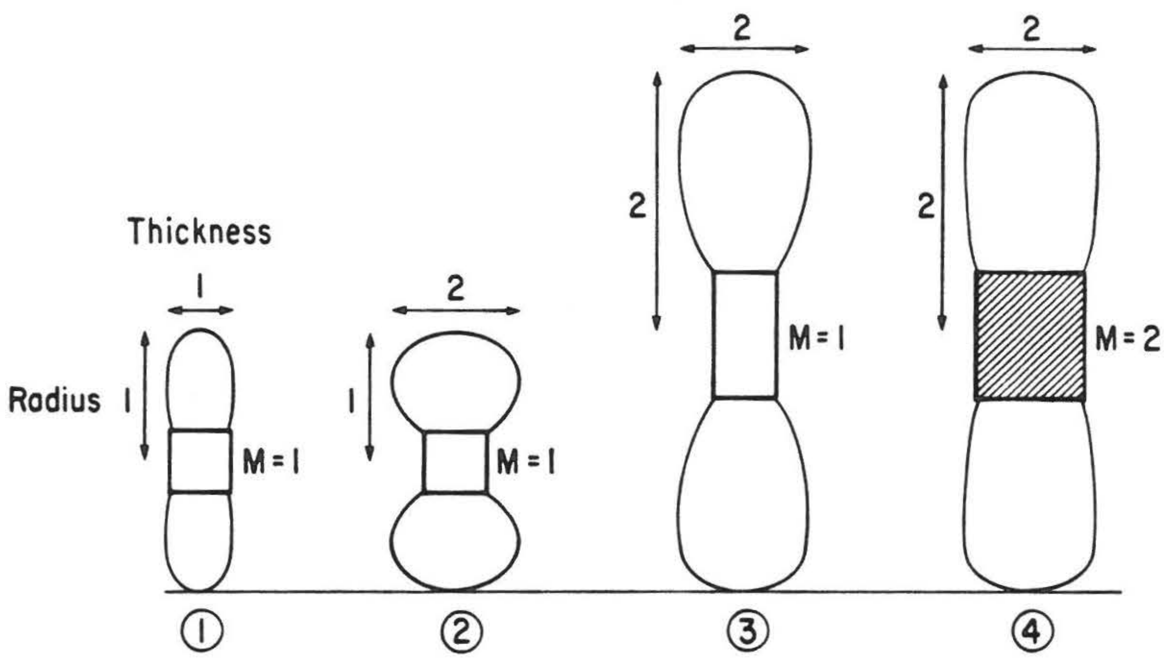

Figure A3. Cross sections of possible alternative wheel designs. Case 1 is the current wheel whose dimensions are taken as unity in the discussion.

We calculate below the predicted power consumption for modified versions of our design. Figure A3 shows three cases, with the original design on the left. Its measures of mass, internal pressure, radius and thickness are defined as unity. If the time for one revolution is held constant, a larger-radius vehicle will travel faster, i.e.,

$$Velocity \propto radius$$

The footprint, pressure differential and mass are related by

$$Mass \times gravity = \Delta P \times footprint \;\; area.$$

We assume that the footprint area is proportional to the wheel thickness and circumference, so the pressure differential will be

$$\Delta P \propto \frac{Mass}{Thickness \times Radius}$$

while the volume required per revolution is

$$Volume \propto Thickness \times Radius^2$$

Analytical calculations show (approximately) that

$$\text{Power} \propto Volume \times \Delta P^{1.6}$$

The relevant parameter, velocity per unit power, is therefore

$$\frac{Speed}{Power} \propto Mass^{-1.6} \times Radius^{0.6} \times Thickness^{0.6}$$

This yields the surprising result that a larger rover should be faster for the same power output. Case 2 in Figure A3, for example, uses sectors which are twice as thick, and therefore has double the footprint area. It would roll about 50% faster than Case 1, the reference design. Case 3 doubles all the inflatable dimensions (while keeping the mass at 500 kg); such a rover would travel 2.3 times faster than the nominal case. The fourfold decrease in pressure differential (allowed by the corresponding increase in footprint area) more than compensates for the increased volume of the wheel. If, however, the vehicle mass also increases by a factor of 2 (Case 4), the relative speed is only 87% of the reference case. It might still be favorable to scale up the vehicle size for improved obstacle negotiation.

It is important to keep in mind that these calculations are extrapolations from current performance. Many aspects of the current behavior were unexpected, and the above scaling relationships should be viewed with caution. The concept of the footprint, for example, is oversimplied. In Section 6.2.5, we conclude that a high pressure-to-weight ratio (hence *smaller* footprint) is desirable for lateral stability. It may not be possible, therefore, to simply increase the footprint to lower the pressure differential. Further experimentation with scale models may be required. In addition, we have assumed that the compressor efficiency does not depend on pressure differential; if compressors are significantly more efficient at low pressure differentials, then low-mass/large-footprint vehicles are even more favored.

The rough requirement of 90 to 180 watts is within the capabilities of solar cells. Based on the Viking Orbiter solar cell efficiency, an area of 2.25 to 4.5 square meters could supply the necessary power [12]. Recent developments with photoelectrochemical cells have shown efficiencies near 11% [13]; if such cells are practical on Mars, only 1.3-2.7 square meters would be required.

Three results of these calculations bear repeating: (1) The largest uncertainty in the calculations is the efficiency of the compressor operating under Martian conditions; (2) Vehicle mass is quite costly in terms of power consumption, and all efforts should be made to keep it at a minumum; (3) Our calculations show that a reasonable area of solar cells might meet the power requirements for propulsion.

APPENDIX B: Mars Ball Project Participants

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