DESIGN OF A WIND POWERED MARS ROVER

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ABSTRACT

There has been considerable interest in the unmanned exploration of Mars for quite some time [4][7][8] but the current generation of rovers can explore only a small portion of the total planetary surface. One approach to addressing this deficiency is to consider a rover that has greater range and that is cheaper so that it can be deployed in greater numbers. The option explored in this paper uses the wind to propel a rover platform, trading off precise navigation for greater range. The capabilities of such a rover lie between the global perspective of orbiting satellites and the detailed local analysis of current-generation rovers. The design of the Wind-Powered Mars Rover is discussed, and the prototype built at McGill University as part of a student design course is described.

Keywords: Mars, Wind-powered, Rover

ROVER À PUISSANCE ÉOLIENNE POUR L'EXPLORATION DE MARS

RÉSUMÉ

L'exploration sans équipage de Mars suscite un intérêt considérable depuis un certain temps déjà [4][7][8], mais la génération actuelle de rovers ne peut explorer qu'une légère portion de la surface totale de la planète. Il existe une approche pour aborder cette lacune, à savoir envisager un rover qui aurait une plus grande portée et qui serait moins cher pour qu'il soit possible d'en déployer en plus grand nombre. L'option explorée dans le présent article fait usage du vent pour propulser une plateforme de rover, échangeant une navigation précise pour une plus grande portée. Les capacités d'un tel rover reposent entre une perspective générale de satellites orbitaux et une analyse locale détaillée de rovers de la génération actuelle. Le design de rovers éoliens sur Mars est abordé et le prototype construit à l'Université McGill dans le cadre d'un cours sur le design est décrit.

Mots-clés : Mars, propulsion éolienne, Rover

1. Introduction

Mars is the Earth's closest planetary neighbour yet many of its features are still unknown. With an energy and cost efficient exploration vehicle, more Martian terrain could be surveyed, hence leading to a clearer understanding of the origins of the solar system and possibly to the discovery of extraterrestrial life.

Currently, surface exploration of Mars has been carried out exclusively by self-propelled unmanned vehicles that need to devote a substantial part of their weight to carrying their propulsion systems. This limits the range of these vehicles and increases their cost significantly. One proposed solution is to employ Martian winds as the primary mean of propulsion, thus reducing a rover's weight and cost. A whole fleet of inexpensive lightweight wind-powered rovers can then be set to roam freely on Mars. A greater number of rovers would minimize the impact of any particular single failure while drastically expanding the mission's range of exploration. A concept for a wind-powered Mars rover already exists. The *Tumbleweed* is a large spherical rover that was designed by NASA and the Jet Propulsion Laboratory (JPL) [14] that rolls and bounces with the wind. The major disadvantage of this concept is the lack of directional control.

This paper describes a novel concept, a wind-powered Mars rover that incorporates basic directional control functions. The various phases of this project will be outlined, from concept generation and evaluation phase to the construction and testing of a working prototype.

2. Problem Definition

The main objective of the project was to develop a scaled prototype that could be used for testing on Earth but would have performance that was representative of a rover designed for Mars. It should be noted that some of the requirements apply only to the final Mars-bound vehicle (the flight model), and the Earth prototype will only need to fulfill some of these requirements.

The Earth prototype will however need to account for the differences between Mars and Earth in order to properly simulate Martian operating conditions. Mars has unique geographic conditions, especially with regards to a wind-propelled platform. The largest problem is due to the very low atmospheric density, about 1% that of Earth's density [1]. In addition the strength of the Martian gravitational field is a little more than a third that of on Earth.

2.1 - Design for Mobility

Limited range is one of the more significant technical shortcomings of the current Mars rovers. The last two rovers to have been launched by NASA, *Spirit* and *Opportunity*, landed on Mars in January 2004 [6] and at the time of this writing, the vehicles have covered a total of just over 18 km of travel [12]. While this greatly surpasses the vehicle's designed range of 1 km each over a 90-day lifespan, the area explored is only an infinitesimal fraction of the planet's surface.

The wind-propelled rover addresses this concern. This current project follows in the footsteps of previous initiatives carried out by the Jet Propulsion Laboratory (JPL) since the 1970s to develop an inflatable wind-propelled rover. One recent vehicle is the *Tumbleweed*, developed at North Carolina State University. A recent test in Antarctica saw one such prototype travel over 130 km in only two days [13]. While this concept clearly solves the range it lacks control.

In terms of mobility, this design project should provide some degree of control to this inflatable, wind-propelled concept. It is not expected that this prototype be as fast as the *Tumbleweed*, but it will be faster than today's solar-powered, electrically driven rovers. Because the rover is wind-propelled, its direction cannot be controlled with precision or at all times. Thus, its speed and manoeuvrability will both fall between those of the current generation of Mars rovers, and the JPL *Tumbleweed*-type vehicles.

The rover must be able to cover most of the Martian terrain. This includes

- Overcoming inclines of up to 30°;
- Clearing or surmounting obstacles half a metre in height;
- Being able to move in moderate winds.

2.2 - Design for Cost

One of the principal advantages of wind-propelled rovers is its low cost. It does not require many of the complicated drive mechanisms featured in the current rovers. Scientific equipment will likewise be less complex too as it is only meant to provide general information on Mars. These simple rovers can be used to locate an area of interest for more detailed analyses performed later.

Combined with its mobility, inexpensive rovers permit exploration using a large number of rovers. A mission scenario that has been considered for this type of rover sees a fleet of cheap, expendable rovers roaming the surface of Mars and performing general analyses of their respective locations.

2.3 - Design for Transport

The rover should be light and collapsible to facilitate transport, as the cost of a space launch is proportional to the size and volume of the spacecraft. Reducing weight is also important since it would take stronger winds to propel a heavier rover.

2.4 - Design for Durability

While the rover should survive landing on the surface of Mars, its durability requirement for the rest of the mission is much less severe. Because of the aforementioned low cost, the individual rovers can be considered expendable in the case of mass fleet deployment. In this case, the failure of one rover would affect only a small portion of the overall mission.

With this in mind, the rover does not need to survive beyond more than a couple of months.. There are several situations where vehicle loss is expected. During periods of high winds such as those associated with the sublimation of the polar dry ice caps, a rover may be inadvertently blown into canyons or against a particularly damaging obstacle.

2.5 - Design for Self-Sufficiency

A rover should be able to provide its own power for control, manoeuvring, communications, and operation of its payload.

2.6 - Scaling for the Environment

A scale-model prototype is to be built and tested on Earth as a proof of concept. In order to compensate for the extremely low density of the Martian atmosphere, the Earth prototype is scaled down compared to the Mars-bound flight model to place an equivalent aerodynamic wind force on the rover. The aerodynamic force [5][9] is given by:

$$F = \frac{1}{2}\rho A V^2$$

Assuming the average wind speed is approximately equal on both planets, the two variables become the atmospheric density and the cross-sectional area of the rover. Since the density of the Martian atmosphere is about 1% of the Earth's, the cross-sectional area of the actual Mars rover must be 100 times that of the Earth prototype to produce the same wind force. The approximate wheel diameter of the flight model needs to be about 4 m. in order to have the same cross-sectional area as Tumbleweed, so the Earth prototype will have 40 cm diameter wheels.

The target mass of the Mars-bound rover is 40 kg, again replicating the Tumbleweed design parameter. Martian gravity is only 38% of terrestrial gravity, so the rover weighs about 149 N on Mars. To simulate this 149 N weight on Earth, the rover prototype must not exceed 15.2 kg. A payload allowance of 3 kg is required, leaving a maximum rover mass of 12.2 kg.

3. Concept Generation and Evaluation

A functional decomposition of the project was performed to facilitate concept generation. The design problem was decomposed into the following functions: steering; stopping; and auxiliary power generation. Using a morphological chart, concepts were generated and three selected for further consideration. The most suitable design was determined using a Pugh matrix.

3.1 - Functional Decomposition

3.1.1 - Steering

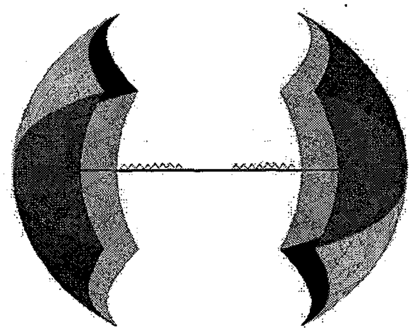

Figure 1 – Umbrella mechanism

Two basic methods were considered for the rover's steering: asymmetrical inflation, and a mechanical expansion/contraction method that was termed the "umbrella mechanism," due to its structural similarity to an umbrella. A sail-type directional system was briefly considered, but a steering system that could also serve as a stopping mechanism was preferred.

For the first method, partially deflating one of the wheels can make the vehicle turn to some angle to the wind. The main advantage of this system is to eliminate the need for a separate stopping mechanism; deflating both wheels will stop the vehicle.

The 'umbrella mechanism' (Figure1) functions similarly to deflation steering, but this design will be structurally complex, and will required powerful motors or solenoids to operate.

3.1.2 - Stopping

In the inflation/deflation concept, stopping can be achieved by simply deflating the rover wheels entirely. An anchoring device was considered, but retracting the anchor will require additional mechanical components, thus increasing the vehicle's complexity and power consumption. Clutches were also considered for both stopping and steering.. This mechanism was eliminated due to its complexity compared to the inflation/deflation system.

3.1.3 - Propulsion and Power Generation

Three main modes of power generation were considered: direct generation of electricity by a wind turbine, solar panels, and using relative motion generators.

Wind power generation [2][3] is dictated by the following formula

$$P = \frac{1}{2}\rho A v^3$$

where P represents the power in Watts, ρ the air density in kg/m^3 (0.02 kg/m^3 on Mars), A the swept area of the blades in m^2, and v the wind speed in m/s.

The average wind speed on Mars is between 2 to 10 m/s. The wind generator has the highest weight to power ratio of all the power generation methods considered. For instance, an *Air 403 Land* wind generator from **Southwest Windpower** with a mass of 6 kg and a swept area of 1 m^2 can theoretically generate 10 W of power on Mars. Compared to a 290 cm^2 12-V solar panel at 0.4 kg, a wind generator will not be an optimal choice. Furthermore, the wind is not constant on Mars, so the rover is likely to experience days without sufficient winds. The sun is a more consistent source of energy, and would be more suitable for this concept.

A third option to develop power would be to indirectly draw energy from the wind via the rotation of the rover. The relative rotational motion between the rotating wheels and parts that do not rotate with respect to the ground could be used to drive a generator and produce electricity. The drawback of the relative motion generator is that the source of power, the wind, is unpredictable and variable. Therefore, the relative motion generator would more likely be used as a secondary source of energy to charge the batteries. The operating principle of the relative motion generator is that the motor shaft is connected to the shaft of the rover (the rotating part). The stator of the motor would be held still as the rotor and shaft rotate. The rotation of the shaft produces a current and a voltage that will charge the battery.

3.2 - Concept Overview

The simplest concept was selected: a rover having two large inflatable wheels steered by inflating and deflating its wheels. Another round of concept generation and evaluation was done to establish the most efficient way to build such a rover. The concept selected incorporates a rotating platform that rotates relative to the ground and a hanging platform below that does not rotate. The hanging platform is elevated for adequate ground clearance. Ball bearings are used to reduce friction between the shaft and the hanging platform. The shaft is rigidly attached to the wheels and turns with them. The rotating platform is also fixed to the shaft and rotates with it. This design provides a simple airtight inflation/deflation system with air tubes going from the wheels to the pump and valves located on the rotating platform. Batteries are stored on the hanging platform, and power is transferred to the rotating platform by the bearings. Keeping the batteries off the rotating platform decreases the rotating moment of inertia. Solar panels can be attached to the exterior of the hanging platform. The hanging platform will act as a pendulum and is self-stabilizing. To prevent the rover from collapsing into itself during wheel deflation, the wheels are attached with large rigid hubs. To protect the rover from the environment, large soft wheels are used for impact resistance, while a rigid, non-porous shell with sealants protect the innards of the rover.

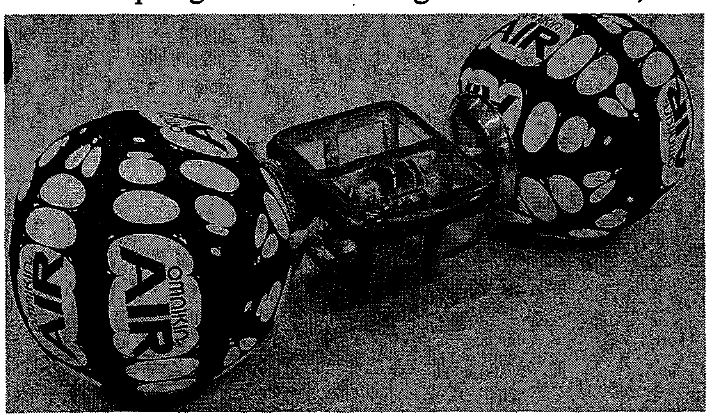

Figure 2 – Final prototype

4. Design Embodiment

An iterative design was used to develop the Wind-Powered Mars Rover prototype. The prototype features a fiberglass hanging platform that remains stable relative to the ground, and is intended to store the payload, including an onboard camera and various scientific instruments. This hanging platform is made from fiberglass tape and is sealed with a 3:2 ratio of polyurethane resin and ceramic additive. It has windows cut out for visibility purposes. The hanging platform houses ball bearings used for smooth shaft rotation, as well as to provide electrical conduction from the power supply (located on the hanging platform) to a centrally located platform that rotates with the shaft. On this rotating platform are mounted a medical-grade micro air pump and three solenoid valves used to control the inflation and deflation of the wheels, along with a receiver and a controller for the radio control system. The pump and valves are remotely controlled by a handheld transmitter. With deflated wheels, its compact volume of 0.05 m^3 (0.5 m × 0.4 m × 0.25 m) makes it a convenient size to transport to the Arctic testing site.

4.1 - Pneumatic System

The pneumatic system is used to control the inflation and deflation of the two inflatable wheels. It is composed of one micro air pump, three magnetically latching solenoid valves and tubing and is controlled via the rover control system. The system is designed to deflate or inflate each wheel independently and to keep the inflatable wheels from deflating when rolling.

The pump used for inflating the two wheels is a Sensidyne AP60 miniature diaphragm air pump [10]. This micro air pump is designed with a compact configuration that allows a minimal system weight and size. This pump can be used for either vacuum or pressure operation, but is only used for pressure operation in this application.

The valves used for the pneumatic system are LHLX0500350B 3-way magnetically latching solenoid valves supplied by the Lee Company [11]. The polarity of voltage to the terminals of the valves controls the state of the valve. The valves were chosen for their small size, low power requirement, and latching capability.

The pneumatic system is setup as shown in Figure 3 where the types of tubing and connectors are also identified. With this configuration, the selector valve is used to control which ball is inflated while the two release valves are used to deflate each ball independently.

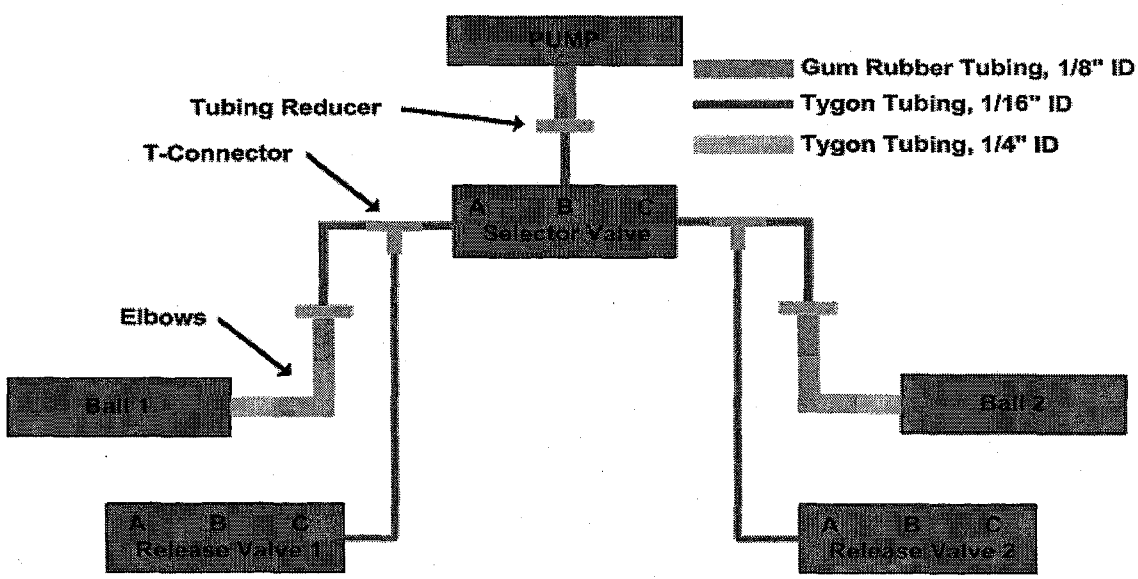

Figure 3 – Schematic representation of the connections between the pump, the valves and the wheels.

4.2 - Drive System

The drive system allows both wheels to rotate and goes from the central rotating platform to the wheels on each side. The two wheels of the rover are composed of two parts: a latex bladder and a nylon cover. The nylon cover attaches to hubs consisting of stainless steel pie plates via laces. Each hub is attached to a machined aluminum coupling, which is fastened to a 3.4" diameter aluminum hollow shaft section. The two shaft sections are connected to the rotating platform via a second set of machined aluminum couplings.

4.3 - Rover Control System

The Rover Control System (RCS) allows the user to control the operation of the pneumatic system, including the valves and the air pump (Figure 4). The system must have a minimum of 4 channels to operate the 3 valves and the pump, and be remotely operated from a distance. The RCS is a modified radio control kit for controlling model airplanes and can operate within a 1 km range. The receiver and controller are mounted to the rotating platform and operate the valves and the pump according to the receiver's instructions. Four 6 VDC battery packs in parallel provide power to all the RCS modules.

5. Test Results

Outdoor testing, in spite of very variable winds in a urban setting, yielded some general results. The rover was capable of moving in gusts of wind. The peak speed observed was 5.6 km/h in approximately 20 k/m wind. As well, the rover was able to turn left and right by slightly deflating

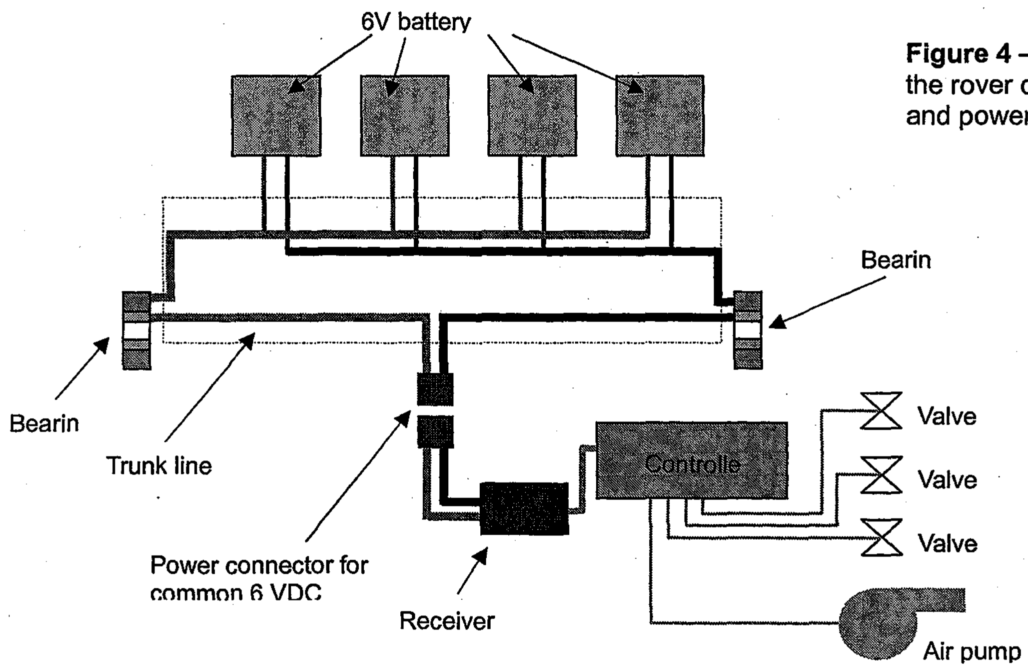

Figure 4 – Diagram of the rover control system and power transmission

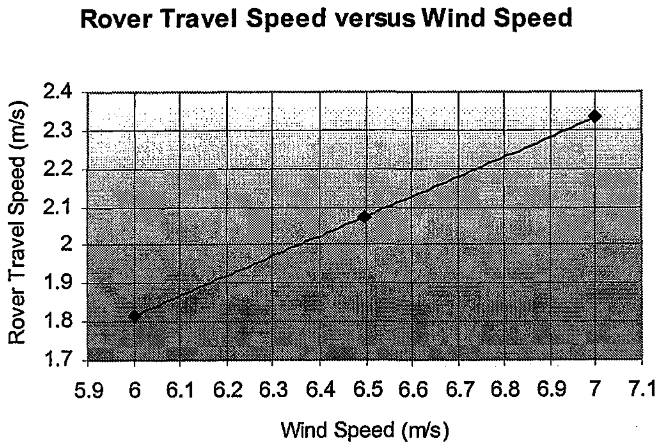

Figure 5 – Rover travel speed test results

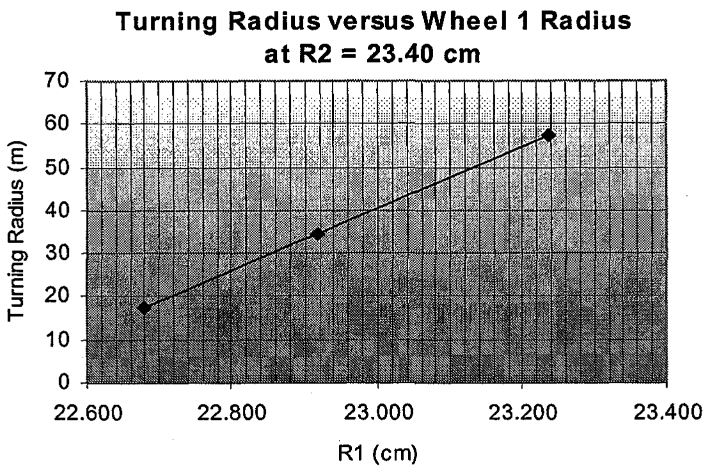

Figure 6 – Turning test results

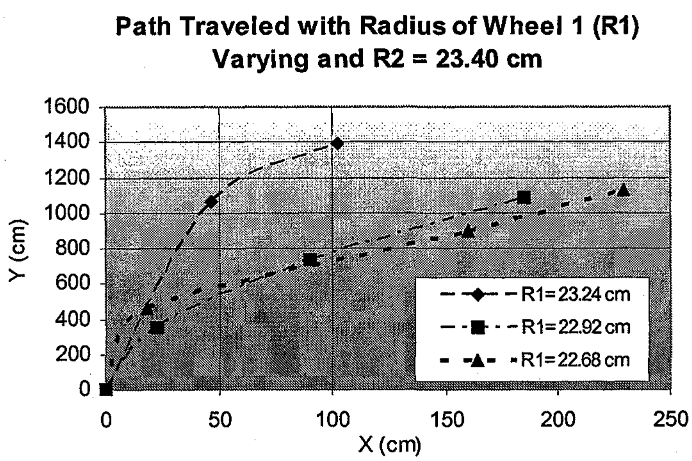

Figure 7 – Turning test results (continued)

the left and right wheels respectively. Finally, with adequate wheel deflation, the rover was unable to move, therefore stopping is possible with enough deflation.

A second phase of testing was performed indoors to obtain quantitative data. Two large ventilator fans were used as the wind source. The wind speed could be altered by changing the distance between the fans and the rover. The fans were mounted on wheels so that they could be moved, allowing a constant distance to be kept between them and the rover resulting in constant wind speeds. Wind speeds were measured with an anemometer.

The first indoor test measured the rover speed as function of wind speed. Both wheels were equal in size and fully inflated. To determine the rover speed, the time needed to travel 8.5 m was recorded. Tests were done at wind speeds of 6 m/s, 6.5 m/s and 7 m/s. The rover speed was observed to increase linearly with wind speed as shown in Figure 5. The rover's speed was calculated to be approximately 30% that of the wind's.

The next test measured how much the rover turned as a function of wheel size. One of the wheels was kept constant in size while the other was reduced to 3 different sizes. Fans were kept at a 1 m distance from the rover during turning, and the trajectory of the rover was traced by recording either 3 or 4 different points. Smaller turning radii were measured as one wheel was reduced in size as seen in Figure 6. From Figure 7, it was observed that after initial turning, the rover's path straightened.

In a test simulating varying crosswind conditions, the fans were angled at a 23° crosswind, which was then increased. The wheels were fully inflated with a radius of 23.48 cm. For a 6.5 m/s wind, the rover moved in a straight line relative to its starting position in crosswinds ranging from 23-65°. At 65°, the rover moved with great

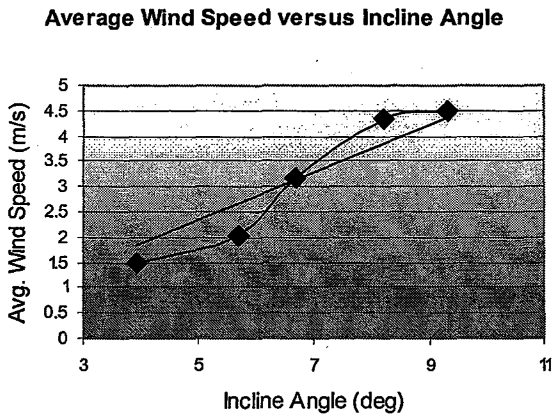

Figure 8 – Climbing incline test results

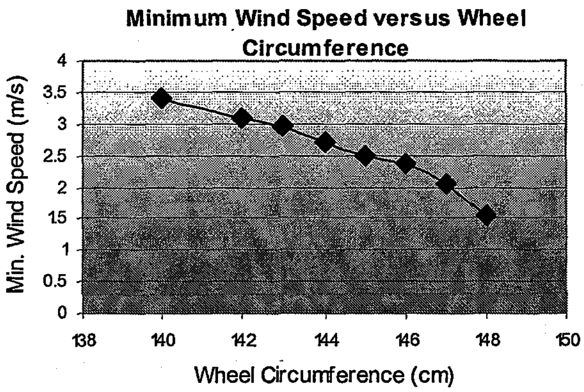

Figure 9 – Stopping test results

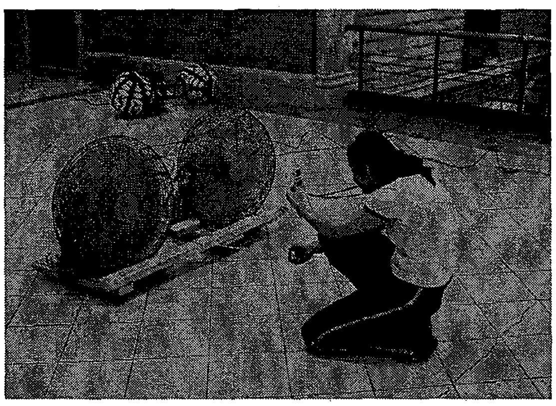

Figure 10 – Indoor test setup, wind speed measurements are taken.

difficulty, so this angle is the approximate critical crosswind angle.

The relationship between wind speeds necessary for the rover to roll up an incline was also tested. The rover was placed on 5 different inclines and the fans were advanced until the rover was capable to remain balanced on the incline without holding it. From Figure 8, the wind speed needed increased non-linearly with the angle of inclination.

The final test measured the amount of deflation needed for the rover to stop. To perform this test, both wheels were completely inflated and then had both their circumferences reduced in 1cm intervals. At each interval, the rover was placed as close to the fans as possible so that it did not move. The associated wind speeds were then determined. The minimum wind speed for the rover to move decreased with increasing wheel circumferences as seen from Figure 9.

A clear source of error lies in the difficulty to position the fans to maintain equal forces acting on each ball especially when having to move the fans to follow the balls throughout the tests.
As a result, the wind speed was measured at each wheel and then averaged.

6. Conclusion and Recommendations

The final prototype not only satisfies all the customer requirements but also performed well during field testing. The conclusions of the field tests are as follow:

- Minor changes in wheel radii are required to obtain large changes in turning radius.
- The more a wheel is deflated with respect to the other, the tighter the rover turns.
- The rover can move away from the wind at angles up to 65° as seen in the crosswind experiment.

- The rover is capable of climbing inclines with sufficient wind speeds. Based on a linear extrapolation, an incline of 30° would require a wind of about 51 km/h.
- Stopping is done by deflating the wheels. Higher wind speeds require more deflation.
- The rover is unable to move when its axis is parallel with the wind direction, even if one of the wheels is deflated.

The series of prototypes leading to the final prototype allowed an incremental improvement of the various systems included in the Wind-Powered Mars Rover. The resulting prototype fulfills all the customer requirements. the following recommendations should be considered if a future iteration of a prototype is to be built:

- A controller having steady ON/OFF switching capabilities could be used to control the solenoid valves, instead of the sensitive directional control used in the prototype;
- To decrease inflation and deflation time for the wheels, use valves with larger flow rates
- The hanging platform could be made lighter by using less plies;
- Solar panels could be added to recharge the onboard batteries;
- Improvements could be made if design for transport was considered;
- An onboard generator could be used to get electricity from rotating shaft.

It should be noted that the material and component selections made for the final prototype must be re-evaluated for the Mars-bound rover, as both rovers are only conceptually related. Due to budgetary constraints, the final prototype's materials differ from those which could be used on Mars. For example, the fabric suggested for the flight model's wheels is Vectran, a synthetic material used on the *Mars Pathfinder* in 1997. The actual properties of this material are perfectly fitted for Mars. Vectran has almost twice the strength of other synthetic materials, such as Kevlar and Spectra, and performs better at cold temperatures. It has a high impact resistance and a high abrasion resistance.

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