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Windball

part 2

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December 3, 2001

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Contents

Chapter 1

Introduction

1.1 Abstract of the first part

This report describes the 2nd part of a work extending over several semesters. We suppose that the reader is familiar with part I, but the following abstract gives a sufficient background to understand the current report.

Up to now, the main problem of Martian robots has been that, in order to move, they depended on energy supply and communication. So, the aim of this semester[1] project was to study the design of a new kind of robot for Martian space missions: A design that, from the start, integrates the particular characteristics of its target environment instead of suffering from them.

Two key characteristics of the Martian environment are omnipresent winds (average 7m/s, more during storms) and high temperature differences between day and night (50...100°C). So, the following concept was developed: A spherical robot that rolls on the Martian surface, pushed by the wind - the Windball. By way of SMA components that change shape with temperature differences, it can change its form between the day and the night. While it travels at night, during the day it takes on a flat, disk-like form. That allows the Windball to take measures, generate energy and be localised by an orbiter.

Two alternatives were considered: The so-called "Hardball", an open, metallic structure of about 1m in diameter and the "Softball", an inflatable balloon of about 10m (see fig. 1.1).

The short-term goal of this semester project was to answer two questions: Firstly, is the Martian wind strong enough to move the Windball in a rocky environment; and secondly, how can its mobility performance be optimised?

[1] i.e. winter semester 2000/2001

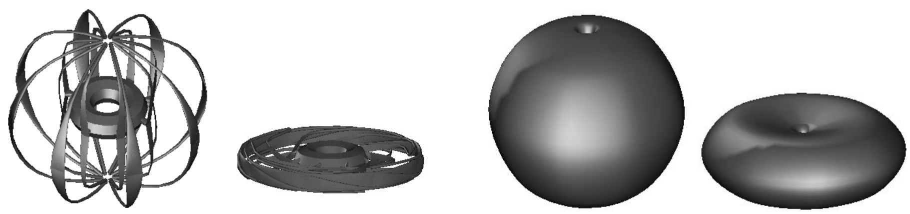

Figure 1.1: The two Windball versions, deployed and folded: the Hardball (left) and the Softball (right)

Two methods were combined to study the aerodynamic behaviour of the Windball: A theoretical model and wind channel experiments.

The model used, in a first step, the laws of aerodynamics to calculate the maximum rock size the Windball could climb over as a function of wind speed and the robot's size. Then, using rock frequency data from Mars, it estimated the mean free path the robot could go in one direction before being blocked by a too big boulder.

In the few experiments that could be performed before the end of this semester we verified the model's predictions about the maximum surmountable rock height. The experiments allowed us, too, to more clearly see the shortcomings of our theoretical model.

From all evidence found we concluded the following preliminary results:

- From the aerodynamic point of view, we are sure the Windball concept will work. In the worst case, it would only move during sand storms.
- At this point, it looks like the Softball performs better than the Hardball. However, this is restricted to the aerodynamic-locomotion problem and needs further verification.

The most important next steps to take are:

- We must make dynamic experiments, i.e. build a to-scale Martian landscape to get a realistic idea of the distance the Windball can go. The mean free path model was found to be too simplistic.
- Other aspects of the overall design, like the shape change or electrical energy production must be studied.

1.2 Motivation

The general motivation for the Windball project is sketched in the abstract in section 1.1: Tackle the tough Martian environment by inventing a robot design that takes into account the conditions found on Mars from the start (for details see [Hei01]).

The reason to perform a second semester project on the the same subject is easily explained: The problems encountered were just a little more complex than estimated, so that the questions we had asked ourselves have not got a definitive answer yet. That is, we still do not know for sure which Windball to build and if the Martian wind will be strong enough to move it. If the first part of the project gave an idea, we would like the second part to get us as close as possible to a final decision.

1.3 Goals

The motivation has not changed much since the first part, and neither have the goals. The long term goal is still to build a prototype that proves the feasibility of the whole robotic system.

In the short term, we would like to further examine the aerodynamics of the rolling robot in order to choose the most promising design.

1.4 Methodology

Even though in most of the work done we studied the aerodynamic properties of different Windball versions, chapter 2 starts out with a more general description of the requirements and desired properties of the robot. Then we present the different design variants, giving the motivation for each new design in terms of the properties described beforehand.

In order to study the aerodynamic-mobility problem, a combination of experiments and theoretical modelling was used, both of which go far beyond the simplistic approximations that have been made during the project's first part: The experimental evidence (chapter 3) is used to fit the theoretical model (chapter 4) to reality, while, in turn, the model allows us to generalise the experimental findings. Chapter 5 interprets all gathered data, comments it and examines to what extent the Windball can perform successfully in a Martian environment. To do this, it combines the findings of the aerodynamic study with our knowledge of the conditions on Mars.

In the conclusion, we will attempt to answer the two questions, i.e. *if* the Windball can work at all, and *which* Windball should work best; finally, we will indicate the next steps to take towards a more general treatment of the overall feasibility.

Chapter 2

Design

2.1 Desired properties

For the Windball to be successful, it must be able to move over considerable distances, securely stop its movement in certain intervals and, while resting, take measurements and transmit the data to an orbiter. Accordingly, there are three property blocks: displacement, stopping and functionality (i.e. measurements and data transmission).

- displacement
  - high wind resistance in displacement mode
  - low rolling resistance, no getting stuck with rocks
  - low weight
  - good shock resistance
- stopping
  - easy shape change
  - low wind resistance in resting mode
- functionality
  - easy energy generation
  - low need for energy storage
  - capability to carry and apply analysis devices
  - capability to communicate with orbiter

2.2 Design catalogue

2.2.1 The Hardball

The Hardball is the original idea of the Windball. It is supposed to have some open, metallic structure that can be folded to form a flat, disk-like shape. The shape change is achieved by shape memory alloy (SMA) actuators (see [Way90]

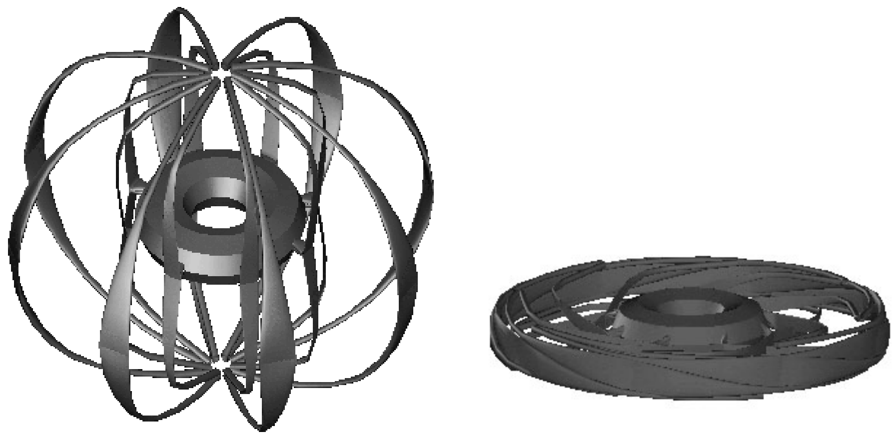

Figure 2.1: The original hardball: deployed (left) and folded (right)

for a brief introduction to their properties). Figure 2.1 shows a sketch of one possible realisation of such a design.

We quickly realised that, in order to get a reasonable forward force from the wind, we would have to use a shape that would not let pass the wind as easily as the one presented in 2.1. A flat disk exposed perpendicularly to the wind has got a higher drag coefficient than a solid sphere, so one rather obvious idea was to build a robot made of three disks perpendicular to each other. In doing so, one would wind up with a form that is far from spherical and would not roll very well. So, the disks are put in something like a cage. In that case one might consider changing the shape of the panels only, leaving the cage deployed as suggested by figure 2.2; this should reduce the forces needed during the shape change.

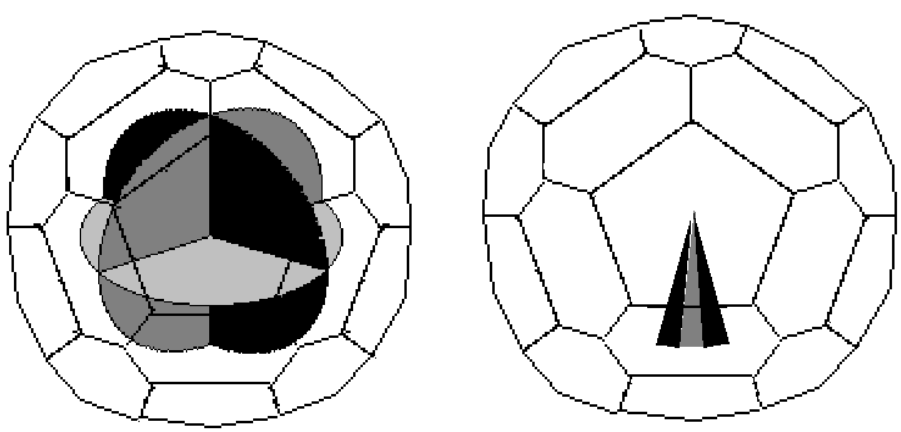

Figure 2.2: The hardball with cage: deployed (left) and folded (right)

Considerations on the Hardball's weight, the wind force and the distribution of obstacles on Mars made us think of about 1 m as being an optimal diameter [Hei01]. We guessed the mass to be between 1 and 5 kg.

We considered the main problems of the Hardball to be the following: Due to the open structure it might get stuck with rocks, and it may be to small and too heavy to roll over the rocks found on Mars. These considerations led to the second Windball:

2.2.2 The Softball

The Softball (see figure 2.3) is an inflatable balloon and much bigger than the Hardball. While the Hardball's solid structure implies that its weight grows at least with the cube of the diameter, for the Softball we find a square law [Hei01]. That allows us to choose a size of some 10m, so that the obstacles become relatively small.

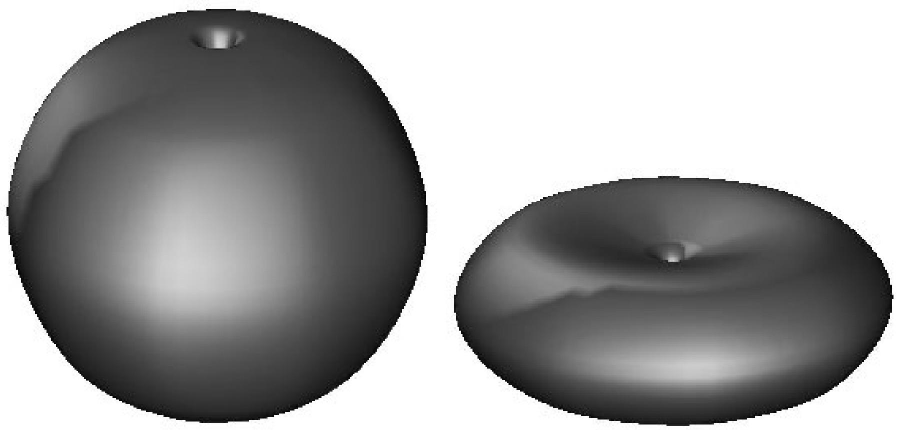

Figure 2.3: The softball: inflated (left) and deflated (right)

The main problem of the Softball is the shape change: in order to securely stop its movement, we would have to deform it, probably even more than suggested by figure 2.3. Several methods have been examined, each of which has its problems:

- If the Softball is deflated, then something like a pump would be needed to re-inflate it. The pump would mean additional weight, it would consume a lot of energy, and the Martian sand would wear the inflation system.
- If the Softball gets deformed, the skin material must stretch considerably. However, that is a contradiction to using light, robust materials like Kevlar.
- If the Softball is flattened *without* stretching the skin material, enormous forces are needed to compress the filling gas.

For the mass of the Softball, we consulted Jack Jones from JPL/NASA, who is building a rover with big, inflatable wheels. His rover's wheels are made of Spectra, Vectran and PBO, weighing 500 g/m^2; as a rolling balloon has got to support its own weight only, he proposed 200 g/m^2 as an optimistic guess.

2.2.3 The Weedball

The Weedball is inspired by the desert plant tumbleweed (see figure 2.4) which forms sphere-like forms that roll driven by the wind. We assumed that its structure would be aerodynamically advantageous, for two reasons: Firstly, natural selection should have done its part, but there was a more direct reason, too: Compared to a sphere, a fine structure like that of a tumbleweed might have a higher effective surface, thus creating more aerodynamic friction; moreover, the friction phenomenon happens at a smaller scale, yielding lower Reynolds numbers Re and possibly a higher drag coefficient c_d (see [Ryh91] for the fluid dynamic background).

Figure 2.4: The tumbleweed, inspiration to the Weedball

A possible problem of the Weedball is its fine and open structure: sand and small stones might accumulate in its openings, making the robot to heavy to move. The shape change, too, seems more difficult than for the Hardball.

2.3 Additional design considerations

Softball with gas-liquid phase change

An alternative idea to achieve the Softball's shape change would be to fill the balloon with a gas that condenses at Martian night temperatures and re-evaporates every morning. Propane or propene could be promising candidates, with their boiling points (231K and 226K, respectively) well in Mars's daily temperature variation range (see [MST] for Martian weather).

This idea has a flaw, as well: The Windball would have to move during the day and rest at night, posing the problem of energy generation for measurements and communication. The very reason to rest during the day was to use solar energy directly, without the need to store it.

On the other hand, if the liquefied gas does not evaporate till several hours after sunrise, there might be just enough time to take measurements and contact the orbiter, exploiting the rising sun with solar cells.

These ideas are still rather vague and need some deeper examination of the energetic processes involved.

Chapter 3

Experiments

The goal of all experiments and the numerical model is to determine the performance of a Windball in a Martian environment. The ever-same question is if a certain wind can move the robot in a sandy terrain with slopes and obstacles. Figure 3.1 shows the logical structure of our approach.

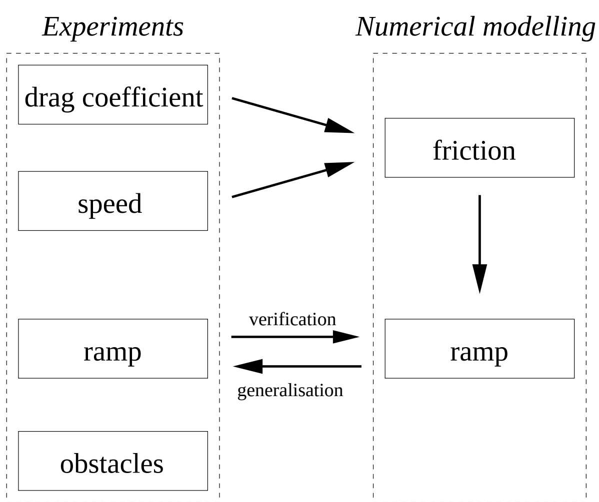

Figure 3.1: Schema showing the logical structure of the interaction between experiments and numerical modelling

The measure of the drag coefficient and the speed of the Windball provided the necessary data to adjust the friction parameter of the numerical model. Then, we applied the model to the problem of the robot rolling up a ramp.

Ramp experiments serve as a verification of the numerical results for the same problem, while the model, in turn, may be used to generalise the experimental findings.

The experiments with obstacles do not have a modelling equivalent (yet).

3.1 Static

Goal

The goal of the static experiments was to measure the drag coefficient c_d. This had two purposes: on the one hand to use this value in the numerical model, on the other hand to make a preliminary choice on different robot designs.

Setup

The drag coefficient c_d was measured in a wind channel using a balance designed for that purpose. See figure 3.2 for the whole experimental setup.

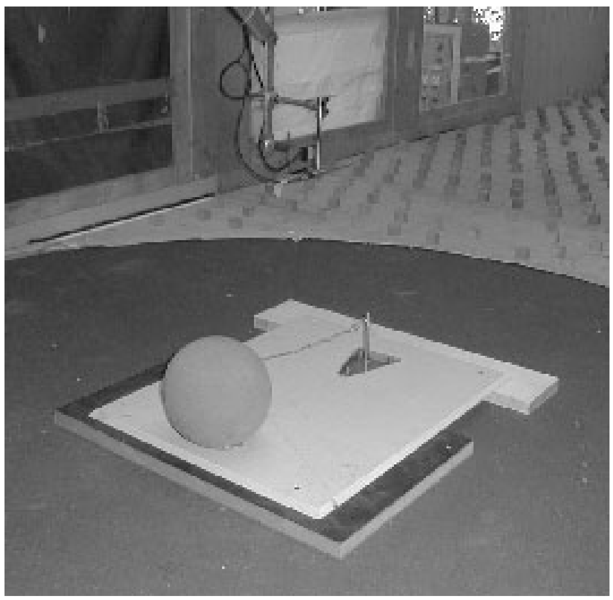

Figure 3.2: The setup to measure the drag coefficient: a Softball model is attached to the balance; in the background, the hot wire anemometer used to measure the wind speed

Models for each Windball type were tested (Hardball, Softball and Weedball); a Softball model can be seen in figure 3.2, see figures 3.3 and 3.4 for the others.

The fan was run at different speeds, while the wind speed and the forces exerted on the balance by the Windball were recorded on-line by a computer.

Observation

See figure 3.5 for the results.

As a mean value to be used in the theoretical model, the following c_d values were extracted: Softball 0.4 and Hardball 1.1. The Weedball design was given up, so no specific c_d was fixed.

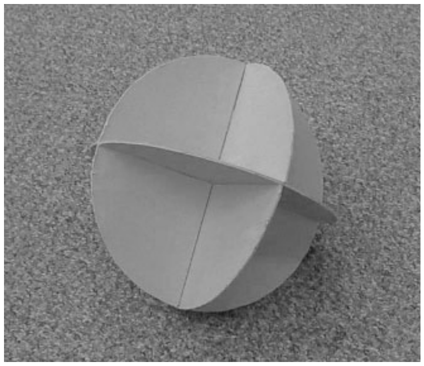

Figure 3.3: The Hardball model for the c_d measurement

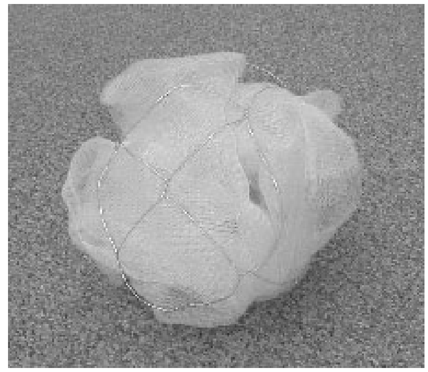

Figure 3.4: The Weedball model for the c_d measurement

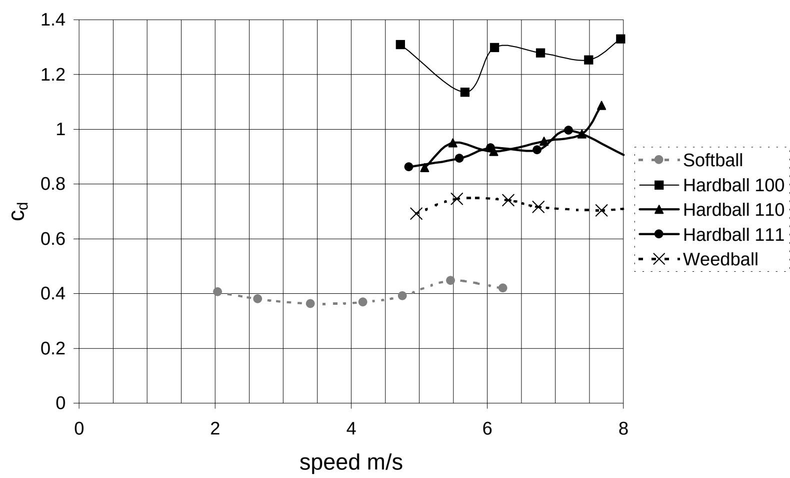

Figure 3.5: Drag coefficient c_d of different Windball types. The three Hardball datasets 100, 110 and 111 correspond to different axes that were parallel to the wind direction: 100 is an axis parallel to the intersection of two disks, 110 lies diagonally in a disk, and 111 is diagonal to all disks

3.2 Dynamic

The dynamic experiments were conducted in a big wind channel (28 m x 2.50 m x 2 m), working at a reduced scale of 1:20. Using this scale, we find the same Reynolds number *Re* for model and reality, so that the aerodynamic phenomena will be similar between the two [Ryh91]. If we take into account the differences in atmospheric pressure, viscosity and gravity between Mars and Earth, and applying the scaling laws presented in [Her95] and [Hei01], we have the following values for the size, speed and mass scales, respectively:

$$\frac{x_e}{x_m} = \frac{1}{20} \tag{3.1}$$

$$\frac{v_e}{v_m} = \frac{1}{2.747} \tag{3.2}$$

$$\frac{m_e}{m_m} = \frac{1}{121.9} \tag{3.3}$$

Using these values, the wind channel experiments are a true representation of the complete dynamic behaviour.

The miniature Windball models used are representations of the Hard- and the Softball (see figures 3.6 and 3.7).[1]

Figure 3.6: The Hardball model for the dynamic experiments

3.2.1 Speed

Goal

The goal of the speed experiments was to determine the rolling friction. As a matter of fact, knowing the drag coefficient, the friction coefficient is the last remaining unknown parameter. See section 4.1 for the fitting procedure.

Setup

The setup is shown in figure 3.7

A double light barrier measures the speed of the Windball as it passes. Marks on the ground before the light barrier indicate the distance to it.

[1]Contrary to the Hardball used for the dynamic experiments, the one used for the c_d measurements was not to scale; nor were the wind speeds. It was necessary to use a bigger model and higher wind speeds in order to obtain measurable forces. That means that we

Figure 3.7: The experimental setup for the speed experiments; on the left, the 3 reflectors of the light barrier, in the foreground, a Softball model

Execution

The quantity we measured was the Windball's speed as a function of the wind speed and the distance run before reaching the light barrier. So, a certain wind speed was fixed and the Windball was allowed to start at a certain point before the light barrier. The double barrier allowed us both to see an acceleration and to extract two speeds for two different distances in every run.

Observation

Figures 3.8 and 3.9 show the results obtained for two different speeds and various Softball models.

The Hardball accelerates over a very short distance, so there was no point in trying to establish a distance–speed correlation. Instead, the limiting speed was measured in several runs (see table 3.1).

The high variability is due to the irregular form of the Hardball which is rather far from a sphere.

3.2.2 Obstacles

Goal

The goal of this experiment was to determine in how far the rocks found on Mars will hinder the Windball's movement.

Setup

Representing a Martian landscape at a scale 1:20 is not quite easy. As a starting point, we used the rock size distributions observed at Viking Lander sites 1 and 2 ([Wil97]), using a mean distribution of the two sites. The larger rocks (higher than 4 cm on Mars, corresponding to 2 mm in the wind channel) were classed

measure a c_d at a higher Re than the one we will finally have in the dynamic experiments and on Mars. However, as we artificially introduce turbulence, we may consider Re to be high enough for c_d to be more or less constant.

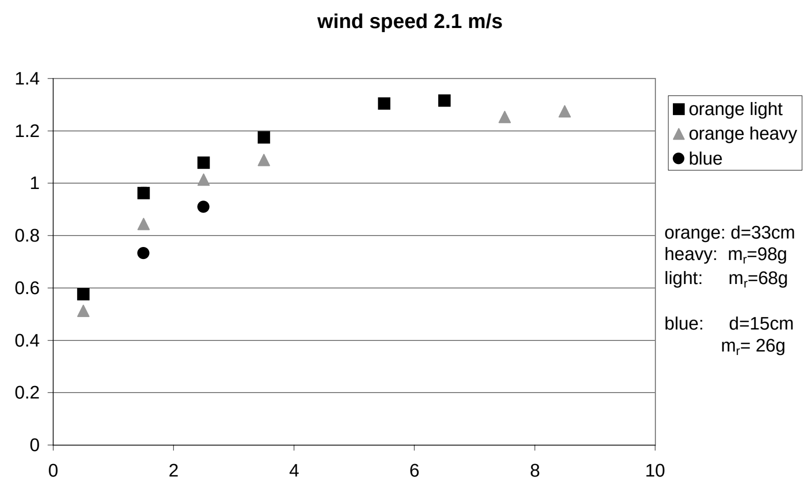

Figure 3.8: Speed as a function of travelled distance for several Softball models at wind speed 2.1 m/s; m_r in the legend is the effective mass reduced by the atmospheric buoyancy

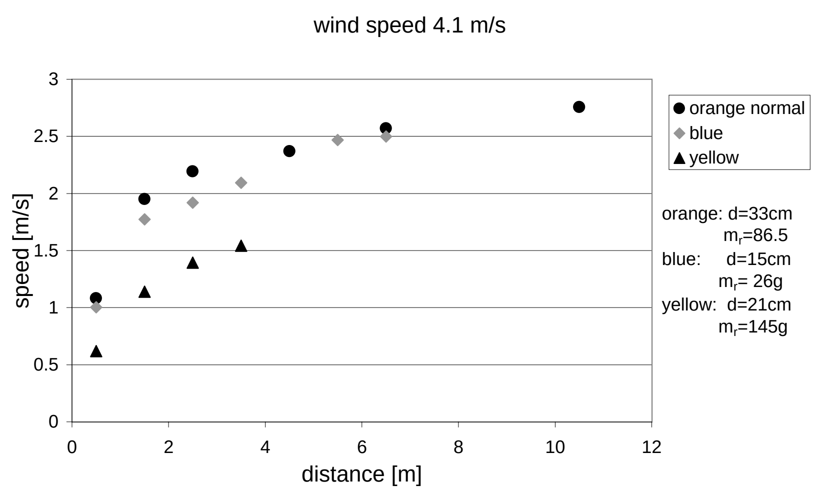

Figure 3.9: Speed as a function of travelled distance for several Softball models at wind speed 4.1 m/s

speed [m/s]	
wind	Hardball
2.1 m/s	0.505
	0.416
	0.338
	0.320
	0.487
	0.427
	0.436
	0.426
	0.395
	0.444
	0.419

Table 3.1: Hardball speed

in 3 categories and we used stones and gravels for them, sorted by size. As the wind channel works in aspiration mode, we could not introduce sand or dust in it, so that we had to represent the smaller rocks, sand and dust by a tapestry (see figure 3.10).

Figure 3.10: The experimental setup for the obstacle experiments with the Hardball model (left) and a Softball model (right)

Execution

We were not really measuring any physical quantity, but rather observing the behaviour of the Windball, trying to learn something from it.

Observation

The obstacles do not seem to add a great difficulty to the movement because they are too dispersed to really block the Windball. Obviously for the Hardball, being of roughly the same size as the rocks, it is a bit harder to roll around them, while the Softball simply rolls over them.

3.2.3 Ramp

Goal

As suggested by the schema 3.1, the ramp experiments served as a verification of the numerical results for the same problem.

Setup

The same obstacle field as in section 3.2.2 was used; the board that the tapestry is resting on was inclined to form the ramp. It had to be placed where the wind channel's ceiling rises, so that the channel's cross section does not decrease.

Execution

This experiment was done with the orange Softball and the Hardball model familiar from the speed experiments. Their masses were adjusted so they corresponded to the expected masses of the originals: The Hardball weighed 9 g (1 kg) and the Softball 231 g (63 kg).

The Windball models were placed at the lower end of the ramp to see if they climbed or not.

Observation

At 2.5 m/s, which corresponds to the average Martian wind speed of 7 m/s, even the slightest slope, combined with the obstacles, left both Windballs immobile.

At 3.6 m/s (10 m/s on Mars), the Hardball would not climb, but the Softball managed 4.4°.

Chapter 4

Modelling

4.1 Presentation of the model

The numerical model simulates a rolling Windball in a constant, homogeneous wind flow. While the Windball's rotation is accounted for in terms of rotational inertia, the aerodynamic consequences are neglected. The ground has no obstacles, but a ramp can be simulated.

We take into account the three governing forces acting on the Windball, projected in its moving direction:

- the aerodynamic driving force $F_{aer} = \frac{1}{2}\rho \cdot (v_{ball} - v_{wind})^2 \cdot c_d$
- the gravity $F_g = m_r g \cdot \sin\alpha$
- the rolling friction $F_f = \eta \cdot m_r g \cdot \cos\alpha$

with ρ the atmospheric density, v_{ball} and v_{wind} the speeds, m_r the reduced mass, corrected by the buoyancy, g the gravity constant, η the friction coefficient and α the slope angle.

If we develop Newton's formula $\sum F = m \cdot a$, we get

$$\ddot{x} = \frac{1}{\gamma m} \cdot (-\eta \cdot m_r g \cdot \cos\alpha + \frac{1}{2}\rho \cdot (v_{ball} - v_{wind})^2 \cdot c_d - m_r g \cdot \sin\alpha) \qquad (4.1)$$

while γ is the correction factor for the rotational inertia; for a solid sphere, $\gamma = \frac{7}{5}$; for a shell (a balloon) $\gamma = \frac{5}{3}$.

Apart from the simplifications listed above, assuming the rolling friction to be simply proportional to the weight is a rough approximation.

The model has been implemented using Mat Lab's Runge-Kutta algorithm for differential equations. The script files used can be found in appendix A.

4.2 Fitting

In equation (4.1), the only unknown parameter is η. So, using the data from the speed experiments in section 3.2.1, we can obtain it with a simple curve fit.

Figure 4.1 shows an example: The experimental data was obtained with the orange Softball and a wind speed of 2.1 m/s. The fit yields a friction coefficient of 0.006...0.01. Together with other data at different speeds and with different Softball models we finally fixed a range of 0.007...0.01.

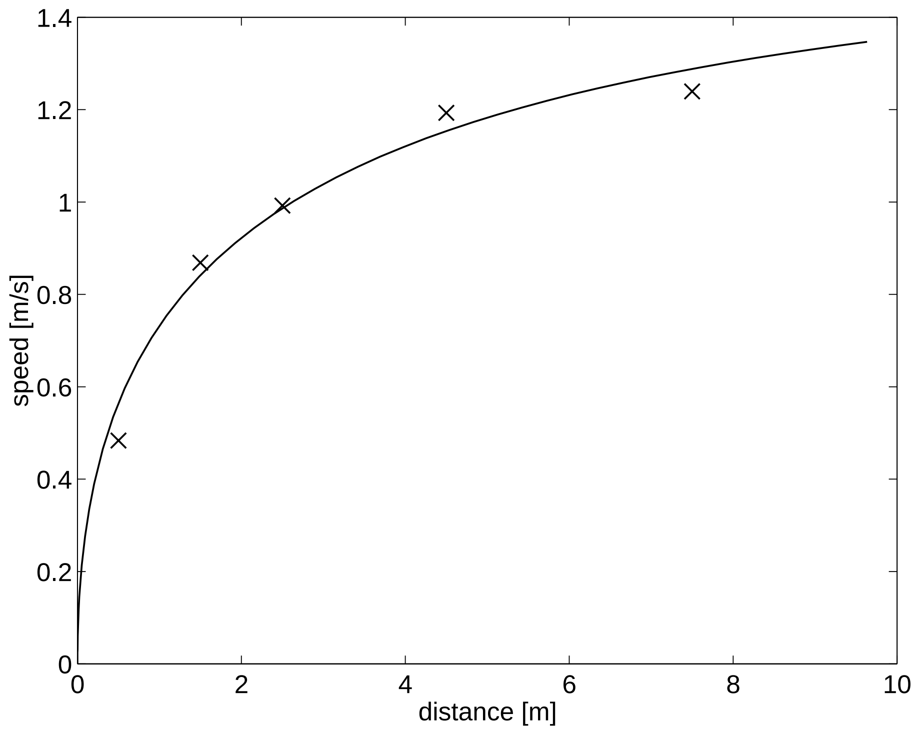

Figure 4.1: Speed as a function of distance travelled: experimental data points and model fit. Example of a Softball model and a wind speed of 2.1 m/s.

For the Hardball, the value is much higher: 0.37

4.3 Application to ramp problem

4.3.1 Static

Here we simply calculated the maximum slope that the Windball could climb without momentum. However, we must bear in mind that not the smallest obstacle is taken into account. See table 4.1 for the results. Figure 4.2 compares the most optimistic scenarios of the Soft- and the Hardball.

4.3.2 Ramp with momentum

In this case we let the Windball hit the ramp with the speed that it reaches after having run a long distance. We calculate, for each wind speed and slope, the height that the Windball can reach, using its momentum (see fig 4.3). The Windballs used correspond to the optimistic versions in table 4.1

type	Softball			Hardball		
	opt.	med.	pess.	opt.	med.	pess.
skin mass [g/m^2]	200	350	500			
mass [kg]	62.8	110.0	157.1	1.1	2	5
cd	0.4	0.4	0.4	1.1	1.1	1.1
radius [m]	5	5	5	0.5	0.5	0.5
friction coeff. η	0.007	0.008	0.01	0.09	0.1	0.37
wind speed [m/s]	max angle [°]					
3.0	0.3	-0.1	-0.3	-4.1	-5.1	-21.5
5.0	1.5	0.6	0.2	-2.1	-4.1	-21.0
7.0	3.4	1.7	0.9	0.8	-2.5	-20.3
10.0	7.4	4.0	2.5	7.0	1.0	-18.9
15.0	17.3	9.5	6.4	22.8	9.4	-15.4
20.0	32.2	17.5	11.9	49.4	21.5	-10.6
25.0	56.9	28.3	19.1	90	39.0	-4.5
30.0	90	43.4	28.5	90	71.9	2.9

Table 4.1: For the Soft- and the Hardball, different scenarios are shown, based on more or less optimistic masses and friction coefficients. For the Hardball, we assumed lower frictions than measured (0.37) because the miniature model used may be improved. A negative value means a down slope is needed to move. 90°means the wind force is stronger than gravity.

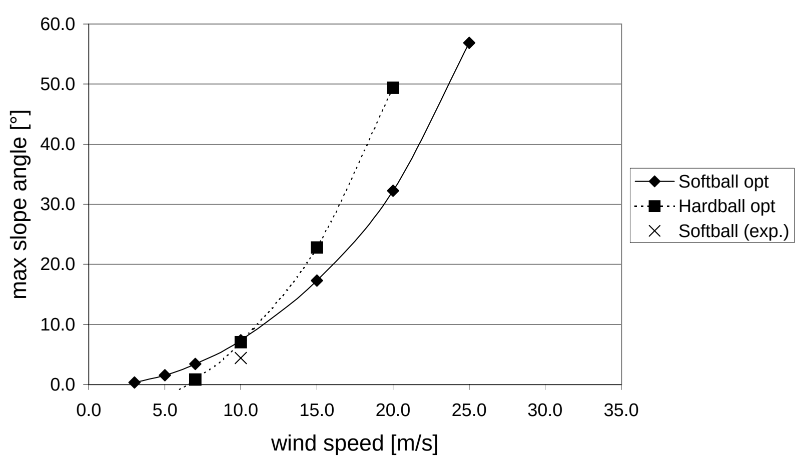

Figure 4.2: Maximum slope the Windball can climb as function of wind speed.

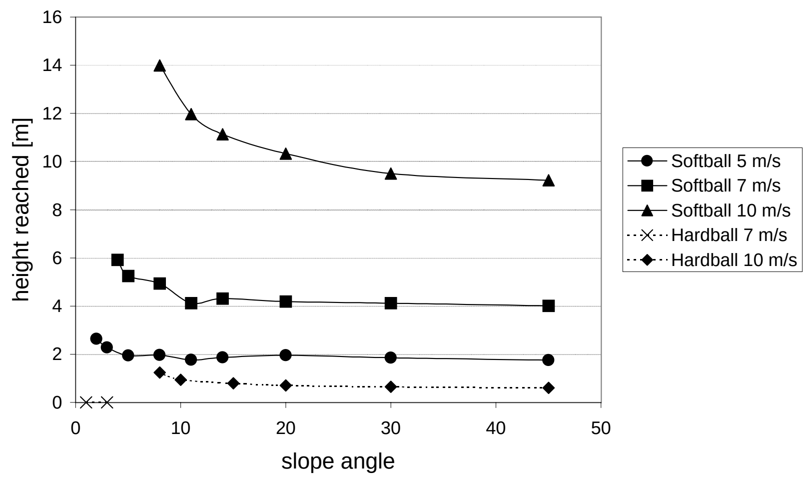

Figure 4.3: Maximum height the Windball reaches when encountering a too steep slope with full speed.

Chapter 5

Evaluation

5.1 Evaluation of experiments and model

5.1.1 Static

c_d measures

While for the Hardball and Softball we find results close to textbook values (cf. [Hoe51]), the Weedball's drag coefficient is deceivingly low. A different model that is more or less permissive to the wind, or has an even finer structure might perform better. On the other hand, looking at figure 3.5, it seems hard to significantly exceed the values of the Hardball.

Maximum slope

The few experiments done on the ramp confirm the prediction of the numerical model fairly well (see figure 4.2). The measured maximum slope is really lower than calculated, as the model does not take into account the obstacles.

Looking at figure 4.2, the comparison between Hardball and Softball shows that, for weak to average winds (<10 m/s), the Softball performs better. For stronger winds, a light Hardball may even outperform a Softball. This is explained by the Hardball's high friction coefficient, which keeps it completely blocked up to a certain wind force.

We must bear in mind though, that the Hardball's rolling friction is mainly due to the imperfection of the miniature model we built. That is why, for our "optimistic" scenario in table 4.1, we assumed an η that is 4 times lower than the one we measured originally. But then, the value is still 10 times higher than for the Softball. Only the realisation of a next-to-perfect Hardball miniature could supply a definite friction coefficient.

5.1.2 Dynamic

Obstacles

As already said in section 3.2.2, a rock distribution like the one we modelled does not pose a real problem for the Windball. That means: if it moves at all, than the rocks will not stop it.

However, the rocks do make it more difficult to climb slopes. It must be verified if it is possible to integrate the obstacles' effect into the numerical model.

Ramp with momentum

The "ramp with momentum" scenario shows that, once the Windball is moving, it can even climb ramps that would be much too steep without momentum. The limiting factor is mostly the height of the ramp rather than the angle (see figure 4.3).

The Softball climbs much higher than the Hardball because it runs faster. On the other hand, the Hardball accelerates *much* faster: The Softball had to run 400 m before the ramp to reach its limiting speed, while the Hardball needed only 10 m.

5.1.3 Weak points of experiments and model

The meaningfulness of our data is limited by both its quantity and its quality.

Too few experiments

While a lot of experiments have been made, there is still a lot of work to do. Some experiments, like the ramp problem, just gave a first idea; they have to be re-done, varying all possible parameters.

Possible improvements of experiments and model

- A better Hardball model has to be built because this is the only way to find a realistic friction coefficient.
- For the numerical model, we must try to find a more complex friction representation, maybe even including rocks.
- We still do not know the exact wind speed profile on Mars; further efforts would have to be made in order to know it *and* simulate it. If the wind at 1 m is a lot weaker than at 10 m, then this will give an advantage to the (bigger) Softball.

5.2 Comparison to Mars conditions

This section combines the abstract findings of our experiments with the conditions found on Mars in order to judge if the Windball can be successful in its environment. It uses data collected shortly before the completion of this report, which is why it is more of a notice than a strictly scientific account. However, we judged the contents too important to be left out.

The critical parameters in the previous sections were slopes and wind forces. While we have not examined any detailed data on slopes and hills on Mars yet, we did find some interesting facts about the winds.

Up to now, we usually assumed an atmospheric density on Mars of ρ=18.1 g/m^3 and wind speeds around 7 m/s. These are, of course, average values. As the Windball's performance under these conditions is rather poor, we must look for regions where the environment is more favourable.

For any point on Mars, the term $v_{wind}^2 \cdot \rho$ is a measure of the wind force. So, we used to the European Martian Climate Database [Col96] to obtain maps of Mars with the wind speeds and the atmospheric densities, at different seasons and different times of the day.

We combined them to maps on which we marked regions where the wind force enables the Windballs to climb slopes of more than 5°. Two major regions were found:

5.2.1 Northern wind belt

During northern winter, there is a belt of strong wind in the northern plains (60°...80°N) all around the clock. However, daily temperature variations are less than 1°C.

During summer, these strong winds disappear.

5.2.2 Equatorial wind spots

Around the equator there are regions, some 1000 km in diameter, where strong winds occur regularly, mostly in the afternoon.

They occur all through the year, but are stronger in northern winter.

Here, temperature variations are up to 80°C.

5.2.3 Consequences

If we do not find a way to significantly enhance the Windball's performance, then we will probably have to choose one of the two regions listed above. Plus, if we want to keep our temperature induced shape change concept, then only the equatorial wind spots are an option. Here, the winds are rather weak at night, so we would have to reconsider our strategy about when to move and when to rest.

Chapter 6

Conclusion

6.1 Feasibility of different robot designs

6.1.1 Hardball

The critical parameters of the Hardball are its rolling friction coefficient and its mass; if our most optimistic assumptions (see table 4.1) are true, then it can compete with the Softball.

Other issues may still pose problems: For example, it is not at all obvious if a shape change by SMA actuation can work at all.

6.1.2 Softball

The Softball is the most promising candidate. Its performance is so that, at least for some regions on Mars, it should work well. The main remaining question is how the shape change can be achieved. The idea presented in section 2.3, i.e. to fill the softball with a liquid whose boiling point lies in the daily temperature range, could be a solution.

6.1.3 Weedball

Given the surprisingly low c_d that we measured, the Weedball has no advantage over the Hardball; on the contrary, given its specific problems listed in section 2.2.3 (accumulation of sand, shape change) we see no point in further development of this idea.

6.2 Next steps to take

6.2.1 Design choice

Neither one of Softball and Hardball performs so well or so badly that it would justify to give up one of them. For the moment, we should continue to develop the two of them.

6.2.2 Design feasibility

The specific problems of the two remaining Windball variants as listed in section 6.1 must be examined. The results of these analyses may eliminate one of them or even both.

Then, a more general engineering approach is necessary, that takes into account a broader spectrum of problems than just the aerodynamic-locomotion problem, like the possibility to generate electricity or to make useful measurements.

6.2.3 More experiments and a better model

As suggested in section 5.1.3, we must repeat and refine certain experiments and try to further improve the theoretical model.

6.2.4 Mission parameters

The detailed analysis we started for the Martian winds should be continued for other environment parameters like the slopes or obstacles on Mars, because this may have unexpected implications on the design requirements.

Acknowledgements

The whole experimental part of this work has been achieved in collaboration with Dr. Jacques-André Hertig. It was made possible thanks to his and his team's know-how and their readiness to share their laboratories and equipment with us.
Special thanks go to Mr. Claude Amendola who fabricated a metal piece by laser cutting technology for us.
Thanks, too, to Professor Peter Monkewitz, who is always open for discussions on aerodynamic issues.
Personal thanks to the whole Autonomous Systems Lab people for their willingness to help with any kind of problem.

Moritz v. Heimendahl *Lausanne, December 3, 2001*

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Appendix A

Mat Lab scripts

General ramp script with Mars conditions

```
global rho;
rho=.0181;   % gas density
global alpha;
alpha=3;     % angle of the ramp
global dist;
dist=00;     % distance to ramp
global length;
length=100;  % length of the ramp
global g;
g=3.7;% gravitation constant
global eta;
eta=.1;
global data;

[T,Y] = ode45('mars_hard',[0 120],[0 -10]);

plot(Y(:,2),Y(:,1),'-');
```

Data for Softball

```
function dy = funk(t,y)
dy = zeros(2,1);% a column vector

m=72.3;         % mass
mr=62.8;        % buoyancy reduced mass
gamma=1.66;     % rotational inertia coefficient
r=5;            % radius
cf=.4;          % drag coefficient
w=10;           % wind speed
global rho;     % gas density
global alpha;   % angle of the ramp
global dist;    % distance to ramp
global length;  % length of the ramp
global eta;     % friction coefficient
```

```
global g;       % gravitation constant
global data;    % experimental data
data=[0.5 1.5 2.5 4.5 7.5;
         0.483666667 0.868666667 0.992166667 1.1932 1.2395]';

dy(1) = (-eta*mr*g*cos(alpha/180*pi)+.5*rho*pi*r^2*cf*(w-y(1))^2-
         heavyside(y(2)-dist)*mr*g*sin(alpha/180*pi))/(m*gamma);
dy(2) = y(1);
```