# SSV Case I


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Building a small solar vehicle

Lightweight


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# Foreword

After a lot of hard work and having met several times a week, the first part of our small solar vehicle, or in short SSV, has been finished successfully. Not only the calculation of every small detail of the SSV was an extremely hard task but also a real experience to extend our knowledge as an engineer. It demanded knowledge of the theory, practice and a lot of persistence.

We don't want to take all the credit because our SSV wouldn't have come to this point without the help of the four coaches. Therefore we want to give a special thanks to Pauwel Goethals, Tan Ye, Yunhao Hu and Pieter Spaepen. These coaches gave a weekly seminar with the information on how to build a SSV. But we want to thank in particular Tan Ye because he was our personal coach who helped us greatly along the way.

Besides the four coaches we also want to thank Marc Lambaerts, FabLab manager, who gave an important and informative session about FabLab. FabLab is the Fabrication Lab where we will build a lot of parts for the SSV.

The project was not an easy project, it was a lot of blood sweat and tears but it was an enormous experience to complete as a student.

We hope you enjoy our report.

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# Resume

This report was written to explain how the the first parts came together.
The entire project can actually be divided into 3 different processes. The first two processes are the analytical stage of the car and the third process is the actual build together with some tests.

The first process is 'case SSV I' which will exist out of the Design, Solar panel and DC-motor, key components of the SSV and Matlab. The other two processes, 'Simulink' and 'case SSV II', and its components can be found as the other two reports.

The first part is actually a very crucial part for the SSV, the design. When the design doesn't work, the SSV will not work. The design was constructed with a combination of different fields of science.

Only a solar panel and DC-motor were given as starting material. Of course these are the most important components of the SSV so a detailed research is necessary. This is the second part of the project, a complete research of the solar panel as well as the DC-motor. This research includes: determining the ideal working situation of the DC-motor, calculating the m-value of the solar panel as well as the maximum power.

The third part consists of the calculation of other key components of the SSV like the gear ratio and absolute mass. These two components are extremely important for the speed and power upon impact. Therefore the two components will not only be calculated analytically but also simulated to determine the ideal values.

The last part of the project is Matlab, this part is also used in the third part to calculate the ideal mass and gear ratio but in this part some additional calculation are mentioned.

# Introduction

The small solar vehicle, SSV, is a small car entirely driven by solar energy which has to resist multiple impacts with a steel ball. This car was built in account of the EE4 project and has multiple goals. Like mentioned before it has to resist multiple impacts but that's not the only or main goal. The SSV has to be a pièce de resistance, a real masterpiece on different levels. These levels are: innovation, speed, strength and looks.

The EE4 project is a project with the motto 'Make stuff work'. As future engineers this is an important part of our set of skills which makes the project of greater value for the students. Not only the part of making stuff work is important but also having the background of different fields of science is crucial like: aerodynamics, dynamics, strength of material, technology of materials, algebra, and energy. These fields will stand out throughout the report.

The needs of all these fields are explained quit easily by explaining the project. The SSV will compete in a race in which it has to accelerate as fast as possible. After having accelerated for 10 meters the car has to face a metal ball of 735 grams which it will have to push as high as possible on a ramp. The car cannot break because it has to compete in multiple races. All the different fields are needed to create this SSV.

The race shows only one of the two important criteria of becoming the best SSV. Like mentioned before, the SSV has to be a pièce de resistance. Therefore it has to look good. This is the second criteria it will be quoted on. The entire design but also the appearance is a crucial part.

This report is written by the members of the team Light Weight who will try to fascinate you with their masterpiece.

# 1. Design

The design of the SSV has a large impact on the performance. To improve its performance, a few important components must be decided: the shape, the building material, the wheels and extra stability.

## 1.1. Shape

The shape of the SSV has a large influence on the speed because when it has a non-aerodynamic shape or when it's shaped like a container it will catch too much wind. Therefore the shape must be chosen wisely to keep the drag coefficient as low as possible. The best shapes are those formed like a tear but this is practically impossible because of the flat shape of the solar panel which has to be on top of the SSV to be in the sun. Therefore the SSV will have the same general shape as a cone. The influence of the drag coefficient is explained in the part about the parameters.

## 1.2. Building material

After having decided the best shape, it's important to decide what the SSV will be made of. Actually this section and the previous section are pretty close because the material will also decide the shape. Not every material can be shaped in the desired pattern.

The building material has to be strong but not too heavy. The strength is needed to survive the 'crash' with the steel ball so it's possible to make the entire car of solid steel but this won't enhance the speed which is necessary to push the ball as high as possible.

The SSV can be divided in three parts for material: the body, the contact material and the wheels. The part about the wheels is discussed in the separate section below.

### 1.2.1. The body

The body is probably the most difficult part to design. It has to be strong, light, easy to manufacture and easy to adjust. The adjusting is needed to mount the motor as well as the gears in the right place. Therefore we will make a frame of wood, which is easy to adjust, not that expensive and strong. For more explanation see section **Design in Solid Works**.

On the wood, it is also possible to install the solar panel. The solar panel has to be able to be directed to the sun to get as much energy as possible. Therefore it will be installed with on a flexible arm, the solar panel is fixed on the arm with a suction cup. This can be seen in the section **Design in Solid Works**.

### 1.2.2. The contact material

The decision of this material wasn't that easy. The material isn't allowed to pass on the shock because then the body will suffer the consequences. The material can't absorb the energy when hitting the ball because then the ball won't roll on the slope. That's why a golf ball seems a good choice. The golf ball is designed to transfer as much energy as possible, this results in a larger travelling distance of the golf ball when hit by the golf club. The coefficient of restitution for a golf ball is 0.83, with a value of zero being a loss of all energy and one a perfect collision in which all the energy is transferred. The golf ball used for the SSV, is a high-compression golf ball, a little bit harder which creates a bigger shock than a normal golf ball, but it will transfer more energy. Because one golf ball isn't the ideal surface to hit another ball, two golf ball will be used, hold together with a steel plate in the front.

## 1.3. Wheels

The wheels are the third crucial component of the SSV, these determine the rolling resistance. When they are very wide, the resistance increases but this is the same for the stability. When decreasing the width, the resistance decreases but the same applies for the stability. Stability is very important because the wheels cannot break upon impact but a larger stability will help prevent the car from swinging along the track.

### 1.3.1. Number of wheels

In the first case, the idea was to use three wheels instead of four but this might not be stable enough so the SSV will drive on four wheels. This decision was made to play safe, when three wheels are not stable enough there would be a giant problem.

### 1.3.2. Radius of the wheels.

The radius of the wheel is actually something that can be played with. This value is used to determine the ideal gear ratio but when the radius changes, the gear ratio changes. So as wheel radius, the value of 4 centimeters is used. This value is based on the height of the ramp and ball. After calculating the gear ratio, it is possible to change the gear ratio when the wheels are already made. This could be done to improve its efficiency.

### 1.3.3. Tires

The SSV has to drive on a rubber surface, so for maximum speed and stability the best rolling resistance coefficient has to be determined. Therefore the following formula was used.

$$Fr = Crr \cdot N$$

With:

- Fr = rolling resistance force
- Crr = rolling resistance coefficient
- N = normal force, the load on the wheels

The resistance force has to be small, otherwise too much power will be lost by friction, but not too small because this will cause skidding wheels what is not efficient. If the main cause was to go as fast as possible, a wheel made of Plexiglas could be used but there has to be enough friction or else the SSV will just slide away when it collides with the ball. As tires, rubber was chosen. Rubber on a hard surface has a coefficient of 0.012 when the wheels have a radius of 4 centimeters, it has enough friction but not too much.
The rolling resistance coefficient can be found in a datasheet for different materials. This value is an approximation because the rubber used to determine this coefficient is probably not the same as the rubber the SSV will drive on.

## 1.4. Extra stability

The car has four wheels to prevent swinging along the track but when the car is not as wide as the track it still can slide from the one to the other side. This can't be prevented without using some extra precaution because when the car is released a little bit to the right it will collide with the right side and swing along the track as seen in Figure 1.

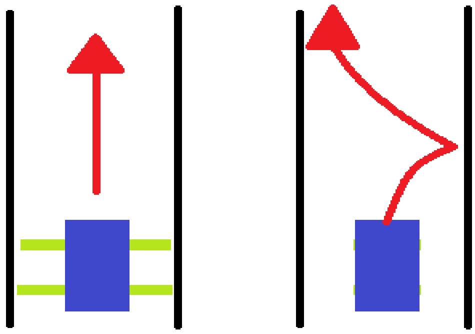


Figure 1: SSV with and without precaution

The blue rectangle is the SSV, the red arrow is the way of travel and the green things are the precautions. These precautions can be compared with arms on a car. These arms touch the wall and keep the SSV on a straight line. Of course it's important that the arms don't touch the wall too hard because this will cause greater friction. The SSV will only have two 'arms', both in the front. This is enough to make sure the SSV will drive straight.

### 1.5. Design in Solid Works

This section will show the design made in solid works and explain the different parts a little further. The design is based on Delta wings (another name for triangular shaped, in this case when the solar panel is mounted it will have the shape of a cone), which is also applied on other aerodynamic cars or planes. The car has the shape of a cone, which is good against resistance from the wind. The delta wings structure is stable and also resistant to high speeds. At the front of the car the golf ball will be mounted which will collide with the ball. In order to keep the ball in its place a carpenter's square is used. The solar panel, mounted on the top, will be bigger in reality, and will influence the aerodynamics negatively. The panel makes it hard to get an optimal shape. A flexible arm is used to mount the solar panel, this way the solar panel can be directed in the right direction which is required to have optimal sunlight. The wheels look like an emoticon, this hasn't aerodynamic benefits or disadvantages but it is the creative aspect of the SSV. The final design can be seen in 'Case SSV II'.

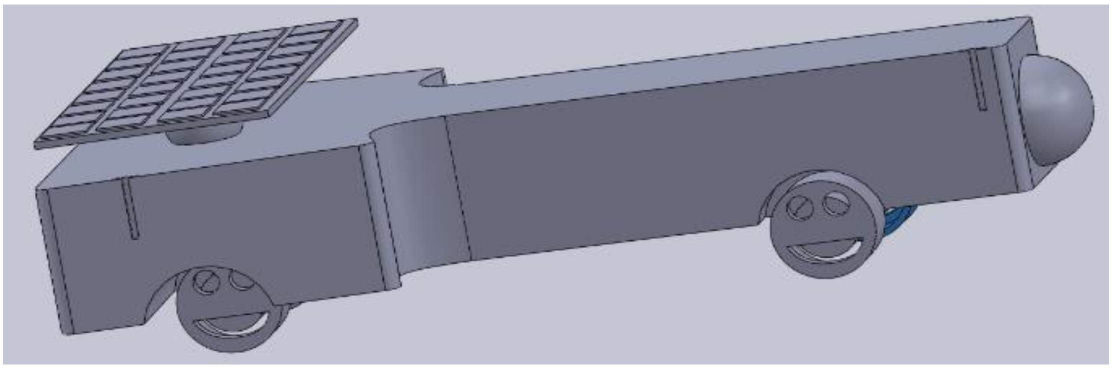


Figure 2: Design in Solid Works

## 2. Solar panel and DC-motor

### 2.1. Characteristics

To get the best results out of the solar panel it is crucial to determine all of its characteristics. This will be done with: a bright lamp, this replaces the sun and provides enough energy, an adjustable resistor and two multimeters.

### 2.2. Goal

The goal of this test is to determine the diodefactor (m) of the solar panel. With this factor it is possible to determine the U-I characteristics and power graph. Together with the U-I characteristics it is possible to determine the working points of the engine at a different rotation speed.

### 2.3. Procedure

First the short-circuit current and open-circuit voltage had to be determined. Therefore a multimeter must be connected in the right way, after determining the current, the open-circuit voltage must be determined.
This was the first step, for the second step an adjustable resistor must be connected. The two multimeters are connected at the same time to measure the current as well as the voltage. The goal is to determine 20 different measurement points and construct a similar graph to the graph seen in Figure 3.
With the results a power graph can be constructed from which we can read the max power produced by the solar panel.
After measuring, it's normal you have to do something with the results. There is a formula to fill in the current and voltage to find the m-value for each measurement point. The formula is:

$$I = Isc - Is \cdot \left(e^{\frac{u}{m \cdot N \cdot Ur}} - 1\right)$$

With
Isc – short circuit current [A]
IS - saturation current [A] (10e-8)
U – output voltage voltage [V]
Ur - thermal voltage [V]: 25,7 mV at 25°C
m - diode factor (range 1~5)
N – number of solar cells in series

First the formula must be written in another form because in this way the result would be a current but something we've measured. Si the formula to calculate the m-value is:

$$m = \frac{U}{\ln\left(\frac{-I + Isc + Is}{Is}\right) \cdot N \cdot Ur}$$

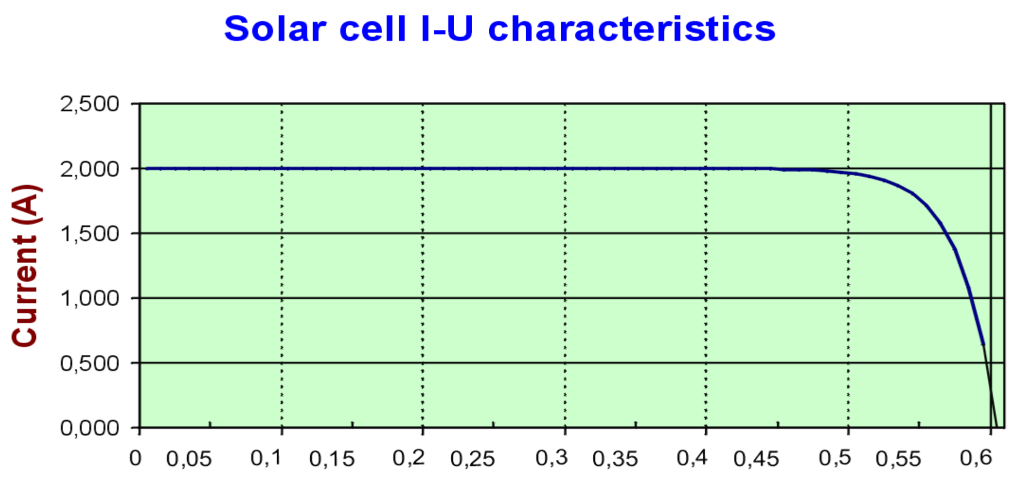



Figure 3: General U-I characteristics

## 2.4. Results and analysis

These are the results after doing the experiment.

Table 1: Measurements of the solar panel

| Measurements | | | | |
|---|---|---|---|---|
| Voltage [V] | Current [A] | Power [W] | | m-value |
| 0 | 0,59 | Isc | / | / |
| 0,46 | 0,59 | | 0,27 | I=Isc |
| 0,93 | 0,59 | | 0,55 | I=Isc |
| 2,88 | 0,58 | | 1,67 | I=Isc |
| 4,36 | 0,59 | | 2,57 | I=Isc |
| 6,63 | 0,59 | | 3,91 | I=Isc |
| 7,25 | 0,59 | | 4,28 | I=Isc |
| 7,36 | 0,55 | | 4,05 | 1,18 |
| 7,43 | 0,52 | | 3,86 | 1,15 |
| 7,49 | 0,47 | | 3,52 | 1,12 |
| 7,55 | 0,43 | | 3,25 | 1,11 |
| 7,65 | 0,36 | | 2,75 | 1,10 |
| 7,66 | 0,32 | | 2,45 | 1,09 |
| 7,71 | 0,27 | | 2,08 | 1,08 |
| 7,74 | 0,23 | | 1,78 | 1,08 |
| 7,78 | 0,19 | | 1,48 | 1,08 |
| 7,79 | 0,16 | | 1,25 | 1,08 |
| 7,8 | 0,14 | | 1,09 | 1,08 |
| 7,8 | 0,12 | | 0,94 | 1,07 |
| 7,81 | 0,05 | | 0,39 | 1,07 |
| 7,9 | 0,02 | | 0,16 | 1,08 |
| 9,35 | 0 | Uoc | / | / |
| | | | Average m-value | 1,10 |

### 2.5. Determining the characteristics of the solar panel: method 1

With these results it is possible to construct a U-I graph as well as a U-P graph which can be seen in resp. Figure 4 and Figure 5. This is the first method to display the characteristics of the solar panel.

The multimeter displayed as short-circuit current 0,59 Ampère and as open-circuit voltage 9,35 volts.

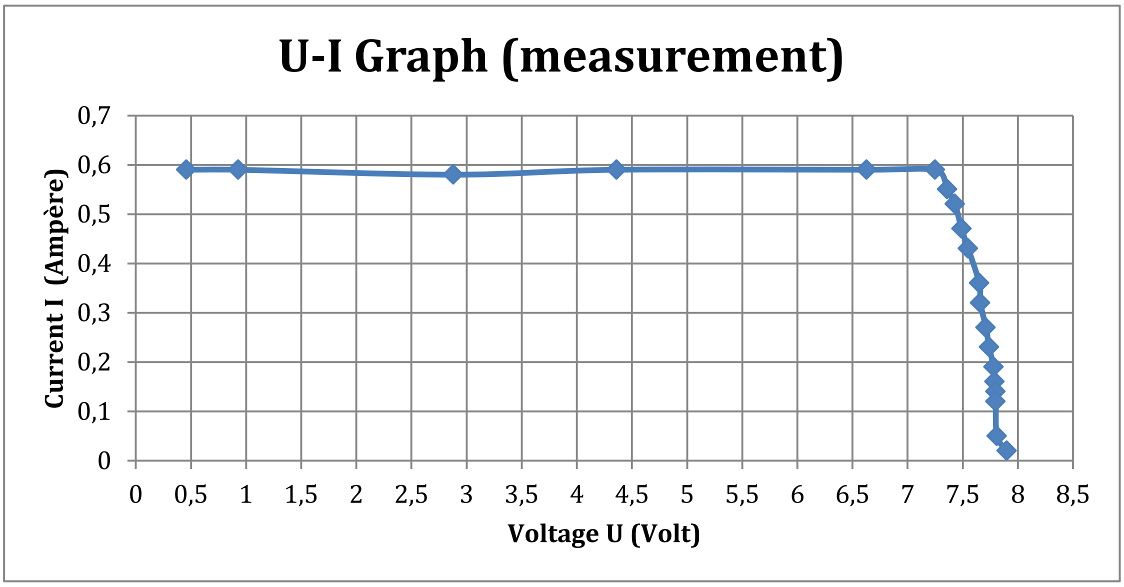



Figure 4: U-I Graph

After doing some calculation in Excel the result for the average m-value is 1,10. This is the average taken of every m-value calculated separately. For method 1 an m-value of 1,10 was found.

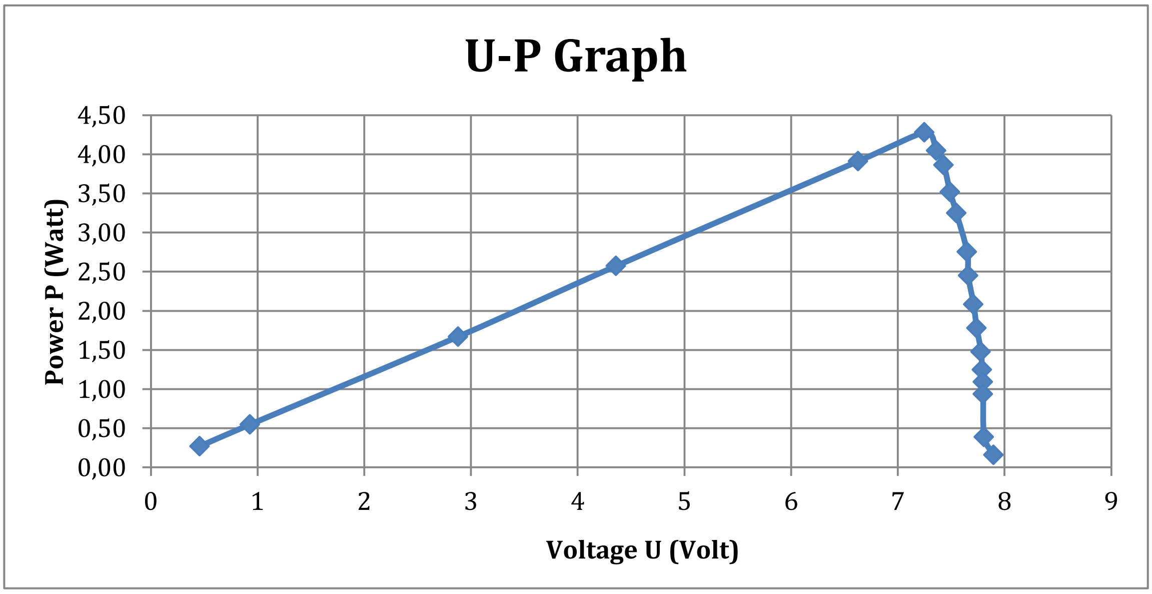



Figure 5: U-P Graph

For extra info about the power see chapter 'Determining max power of the solar panel'.

## 2.6. Determining the characteristics of the solar panel: method 2

As mentioned in the previous chapter there is another method to determine the characteristics of the solar panel. This is a more precise way to find the ideal m-value but actually a method of trial and error.

The procedure is to fill in some m-factors, which are close to the average calculated in method 1, in the Shockley formula ($I = Isc - Is \cdot (e^{\frac{u}{m \cdot N \cdot Ur}} - 1)$). Then the measured voltages will be used to calculate the current. It is this current that will be compared to the measured currents. For a better visualization, different graphs are used. So the main goal of this method is to get a U-I graph which is very similar to the U-I Graph constructed with the measured values. This method will give an m-value which is normally close to the average m-value of method 1.

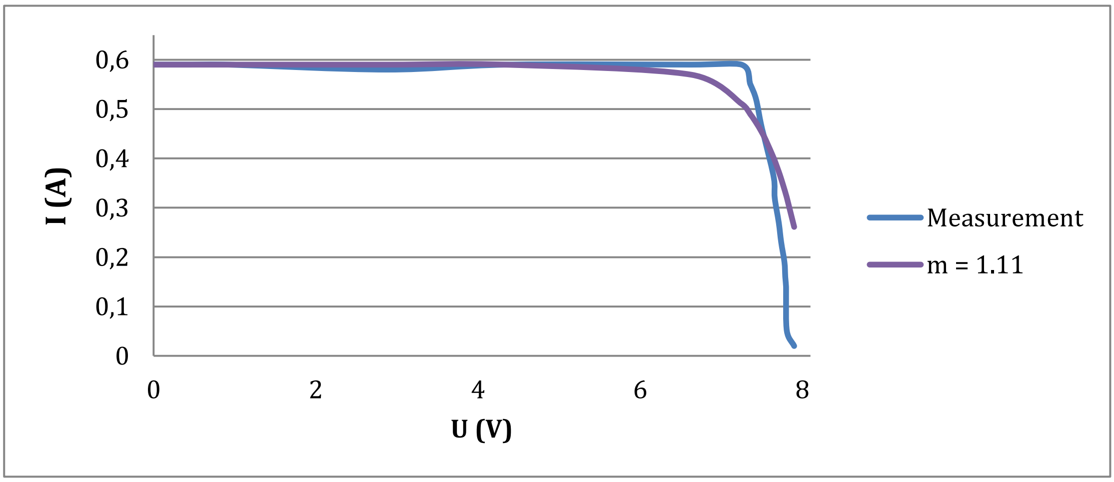



Figure 6: m-value 1.11

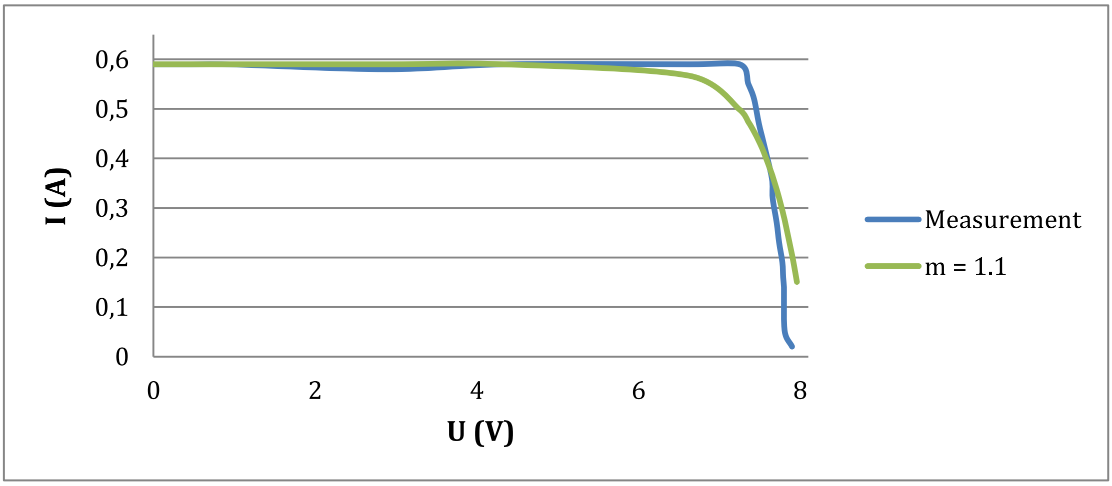



Figure 7: m-value 1.10

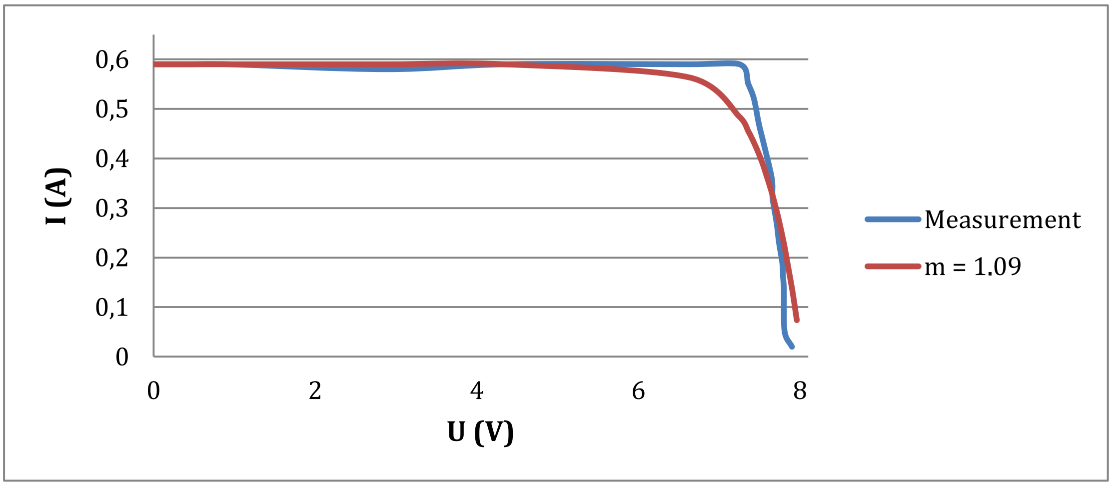



Figure 8: m-value 1.09

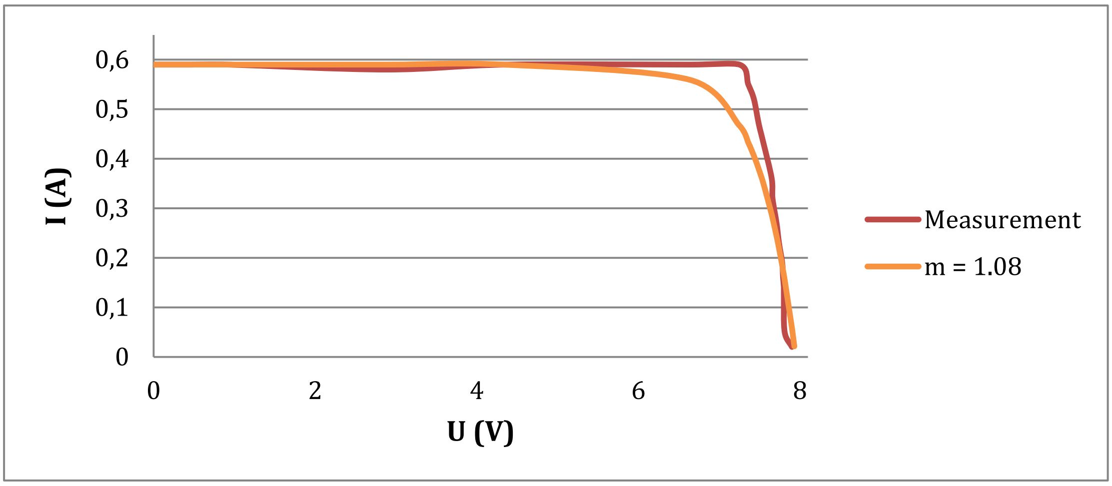



Figure 9: m-value 1.08

The average value, calculated with method 1, is used as starting m-value. At first sight it looks ok but not good enough. To determine the m-factor the beginning value is to be diminished by 0,01 or increased by 0,01. The first graph can be seen on Figure 6. As already told, this method is a trial and error method so multiple values must be tested. When increasing the m-value, the graph started deviating from the U-I measurement graph thus the m-value must be diminished by 0,01 and not increased. The value of 1,08 was the best result, diminishing more resulted in a more deviating graph.

This m-value (1,08) will be used throughout the entire report.

### 2.7. Determining max power of the solar panel

To determine the max power both the measured values of the voltage and current as well as the values of the ideal solar panel are discussed. These two are represented in a graph seen in resp. Figure 10 and Figure 11.

Both the graphs contain some 'errors' so to determine the max power it's necessary to discuss them both. The measurements were done under a bright lamp but the SSV will be powered by the sun so the real maximum power will be slightly higher. For the ideal solar panel the Isc (Short-circuit current) was used as written in the data sheet of the solar panel: 1,03 Ampère. For the measurements the max power is 4,28 Watt and for the ideal case the max power is 6,72 Watt. This value is the absolute max power, but reaching this value is probably practically impossible. This value will depend on the intensity of the sun. The motor operates the best at 5 Watts, but for further calculations the absolute maximum (6,72 Watt) will be used.

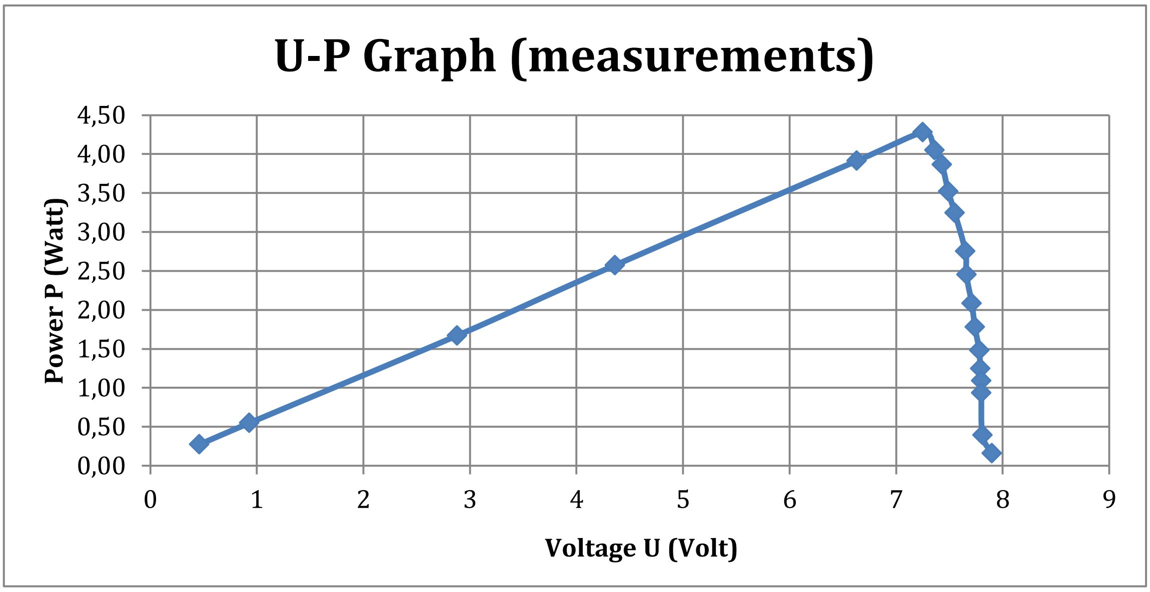



Figure 10: U-P Graph (measurements)

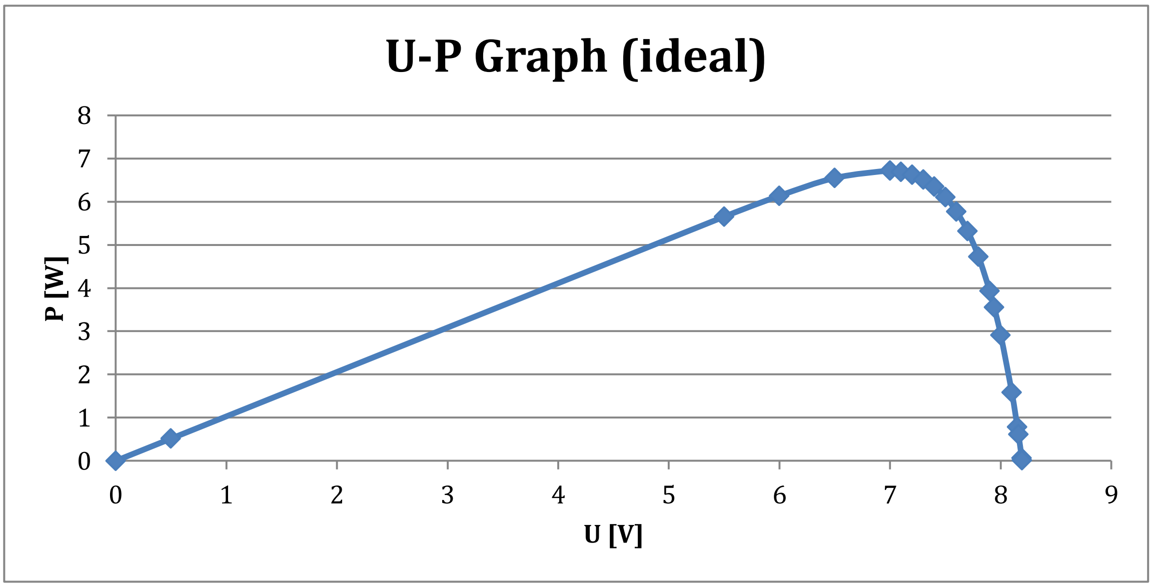



Figure 11: U-P Graph (ideal solar panel)

## 2.8. Operating points of the DC-motor

A DC-motor has its own U-I characteristic that is described by the following formula. For each known voltage and current, there will be a specific rotational speed.

$$U_a = K_e \cdot \omega + R_a \cdot I_a$$

with:

$U_a$ = terminal voltage [V]
$K_e$ = invers of the speed constant [V/ (rad/sec)] = 1120 rpm/V
$\omega$ = rotational speed [rad/sec]
$R_a$ = terminal resistor [Ω]
$I_a$ = supplied current [A]

To define the operating points of the DC-motor the graph of the ideal solar panel must be combined with the U-I characteristic of the DC-motor. This will show what would happen if a DC-motor is connected to the solar panel (physically). The working points are the intersections between the U-I characteristic of the DC-motor and the solar panel. The different intersection point can be seen in Figure 12.

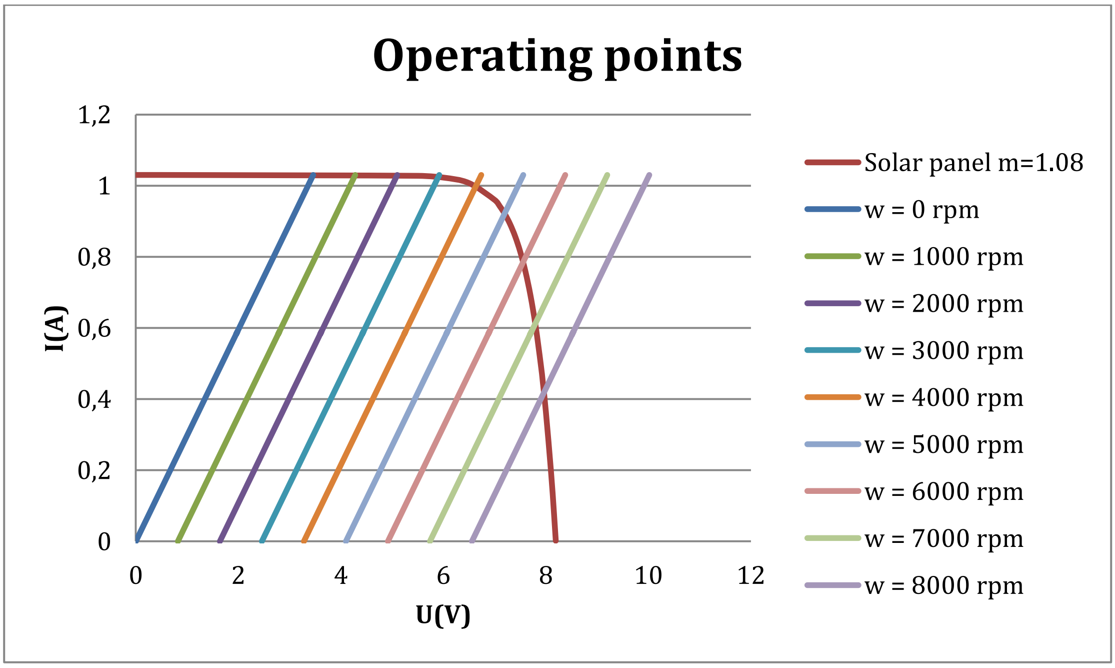



**Figure 12: Operating points of the DC- motor**

This graph, with different intersection-lines, is constructed with various rotations per minute. But it doesn't really tell which number of rotations per minute is the best. Therefore the value of the absolute max power is needed. By using the U-P graph, constructed for the ideal solar panel, it is possible to see that the maximum power produced by the solar panel is: 6,72 Watt. This value is reached at a certain voltage: 6,95 Volt. Based on this information, a new graph can be constructed telling everything that has needed to be known. The graph is shown in Figure 13.

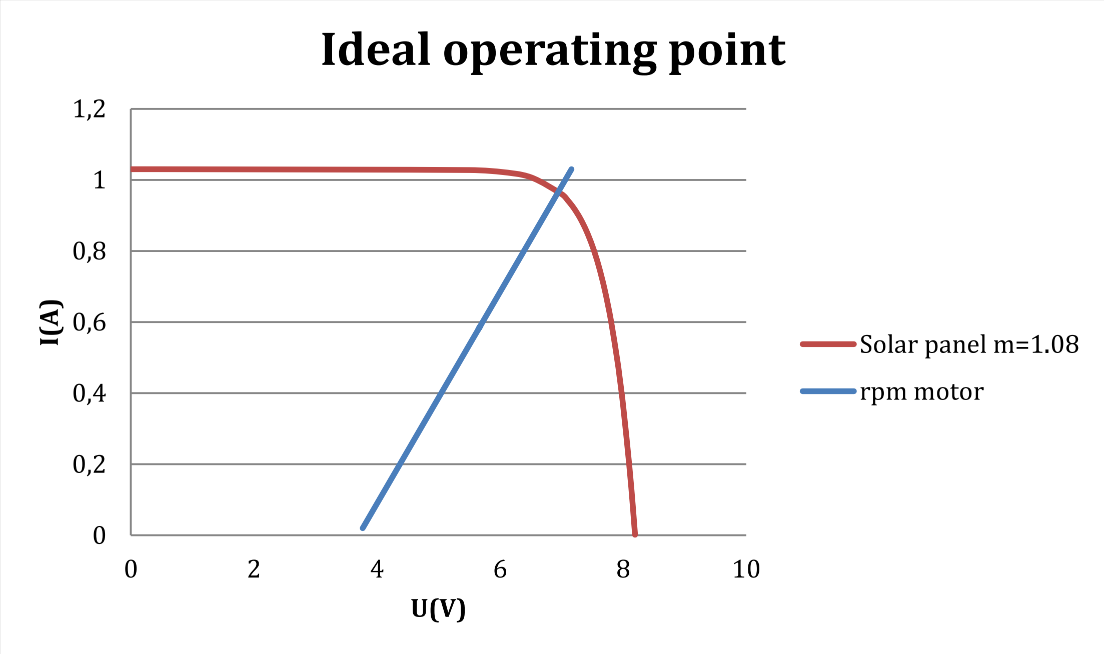


Figure 13: Ideal operating point

The intersection of the two functions is at 6,95 Volt, 0,97 Ampère and the number of rotations per minute is 4514 rpm. That is the ideal working point of the DC-motor. This number of rotation is calculated at the maximum power of 6,72 Watt, of course this is the ideal case. In real life this value might not be achieved.

### 2.9. Error on calculation

Every experiment that is performed carries different errors, with measuring as well as the calculations. To carry out the measurement, two multimeters were used. These two both carry an error of +/- [0,05% + 1 digit], and on the current +/- [2% + 5 digits]. In both cases 1 digit is equal to 0,01. This error is the starting point of the errors within the calculations.

For the calculation of the m-value a formula was used which consists a few constants. The values of these constants are measured at standard conditions. For example, Ur is the thermal voltage and has a value of 25,7 mV at 25°C , the room in which the experiment was done was probably not exact 25°C so these deviations cause errors on the result.

An additional error is caused by us, by reading the value displayed on the multimeter too late or wrong.

The error on the power could be calculated but only the power of the ideal solar panel is used and the values to calculate are written down in the datasheet. Of course it possible to say that the short-circuit current 1,03 A is actually 1,03 ± 0,01. But in this case it's not necessary and this value will be assumed to be exact 1,03 A.

But on the other hand, the m-value is calculated by us with measurement done by us, so this value contains a certain error. This error can be found with the following formulas.

$$\delta m = \sqrt{\left(\frac{\partial m}{\partial U} \cdot \delta U\right)^2 + \left(\frac{\partial m}{\partial I} \cdot \delta I\right)^2}$$

With:

$$\frac{\partial m}{\partial U} = \frac{1}{N \cdot Ur \cdot \ln\left(\frac{I - Isc - Is}{-Is}\right)}$$

$$\frac{\partial m}{\partial I} = \frac{U}{N \cdot Ur} \cdot \frac{\frac{Is}{I - Isc - Is} \cdot \frac{1}{-Is}}{\ln^2\left(\frac{I - Isc - Is}{-Is}\right)}$$

With:

- δm – the error on the m value
- ∂m/∂U – the partial derivative of the m-value to the voltage (this is the same for the other partial derivatives)
- Isc – short circuit current [A]
- IS - saturation current [A] (10e-8)
- U – output voltage voltage [V]
- Ur - thermal voltage [V]: 25,7 mV at 25°C
- m - diode factor (range 1~5)
- N – number of solar cells in series

**Table 2: Error on calculations**

| Voltage (V) | Current (A) | | m-value | error |
|---|---|---|---|---|
| 0 | 0,59 | Isc | / | |
| 0,46 | 0,59 | | I=Isc | I=Isc |
| 0,93 | 0,59 | | I=Isc | I=Isc |
| 2,88 | 0,58 | | I=Isc | I=Isc |
| 4,36 | 0,59 | | I=Isc | I=Isc |
| 6,63 | 0,59 | | I=Isc | I=Isc |
| 7,25 | 0,59 | | I=Isc | I=Isc |
| 7,36 | 0,55 | | 1,18 | 0,007 |
| 7,43 | 0,52 | | 1,15 | 0,004 |
| 7,49 | 0,47 | | 1,12 | 0,003 |
| 7,55 | 0,43 | | 1,11 | 0,003 |
| 7,65 | 0,36 | | 1,10 | 0,002 |
| 7,66 | 0,32 | | 1,09 | 0,002 |
| 7,71 | 0,27 | | 1,08 | 0,002 |
| 7,74 | 0,23 | | 1,08 | 0,002 |
| 7,78 | 0,19 | | 1,08 | 0,002 |
| 7,79 | 0,16 | | 1,08 | 0,002 |
| 7,8 | 0,14 | | 1,08 | 0,002 |
| 7,8 | 0,12 | | 1,07 | 0,002 |
| 7,81 | 0,05 | | 1,07 | 0,002 |
| 7,9 | 0,02 | | 1,08 | 0,001 |
| 9,35 | 0 | Uoc | / | |
| | | | Average error | 0,003 |

In this case the average error equals to 0,003, which is very small. Thus the experiment can be assumed as good and correct.

## 3. Calculation ideal components SSV

There are a few key components that have to be calculated for the SSV to be successful. These key components are the gear ratio and the total mass of the SSV. These are probably the most important components of the SSV, so a comprehensive analysis is needed. Therefore both the gear ratio as well as the mass will be calculated or examined in two ways.

For the calculations some parameters were used:
<u>Solar panel</u>
Isc – short circuit current = 0,9 A
Is – saturation current = 1e-8 A
Ur – thermal voltage = 0,0257 V at 25° C
m – Diode factor = 1,08 dimensionless
N – Number of solar cells in series = 16 dimensionless

<u>DC-motor</u>
R – Terminal resistance = 3,36 Ω
Ce – Inverse of the speed constant = 8,93e-4 V/rpm

<u>Air resistance</u>
Cw – Drag coefficient = 0,5 dimensionless
A – Frontal surface area = 0,03 $m^2$
Rho – Density of air = 1,290 $kg/m^3$

<u>Rolling resistance</u>
g – gravitational constant = 9.81 N/kg
Crr – rolling resistance coefficient = 0,012 dimensionless

<u>SSV</u>
r – wheel radius = 0,04 m

The parameters mentioned in the part of the solar panel and DC-motor can be found in the datasheet or are calculated in the sections above. The density of air and gravitational constant are the values for Leuven. The drag coefficient is the drag coefficient of a cone, this is the most resembling shape of the SSV. The last parameter, the rolling resistance can be found on science websites and is de coefficient of rubber on a hard surface (or rubber) because the track will be made of rubber which is also the material as the tires of the SSV.

### 3.1. Analytical calculations

First the different components are determined analytically, then determined with Matlab.

#### 3.1.1. Ideal mass

To push the steel ball as high as possible, the SSV needs to have a certain mass. Otherwise the SSV will just bounce of the ball, when it's to light, or just move too slow, when it's too heavy. So as a starting point, it's possible to state that the minimum mass must be at least higher than the weight of the ball, which is 735 grams. But further measurements are needed.

#### 3.1.1.1. Calculations for ideal mass

In these calculations all the outside forces are neglected. The gear ratio used is 7,8, as seen in the analytical gear ratio calculations.

First the forces on the motor are calculated, this leads to the wanted expressions for speed and acceleration with the mass included. When these equations are transformed, the ideal mass can be found.

$$F_{as} = \frac{T_{out}}{R_w}$$

$$i = \frac{T_{out}}{T_{in}} \Rightarrow T_{out} = i \cdot T_{in} \cdot 0{,}84$$

Tin=6,36975 ·10^(-3); i=7,8; Rw=0,04m

$$F_{as} = \frac{i \cdot T_{in}}{R_w} = \frac{7{,}8 \cdot 6{,}36975 \cdot 10^{-3}}{0{,}04} = 1.1943N$$

The speed of the solar vehicle can be found by the general equation of linear acceleration.

$$v_{SSV}^2 = v_{0,SSV}^2 + 2 \cdot a \cdot (x - x_0)$$

The SSV starts with a speed of zero at distance zero, this gives:

$$v_{SSV}^2 = 2 \cdot ax$$

$$a = \frac{v_{SSV}^2}{2x} \qquad (1)$$

From the force Fas on the wheels we can determine the acceleration by the wheels

$$F_{as} = m \cdot a \Rightarrow a = \frac{F_{as}}{m} = \frac{k \cdot T_{in}}{m} \qquad (2)$$

These two equations combined gives:

$$(1) = (2) \Rightarrow \frac{v_{SSV}^2}{2x} = \frac{k \cdot T_{in}}{m} \Rightarrow v_{SSV}^2 = \frac{2 \cdot x \cdot k \cdot T_{in}}{m} \Rightarrow k = \frac{v_{SSV}^2 \cdot m}{2 \cdot x \cdot T_{in}}$$

At this point $v_{SSV}$ is still unknown, but $w_{in}$ (= 785rad/s) is known as well as i:

$$\frac{\omega_{in}}{\omega_{out}} = i \qquad \Rightarrow \omega_{out} = \frac{\omega_{in}}{k \cdot R_w}$$

$$k = \frac{i}{R_w} = \frac{7.1}{0.04} = 178$$

$$v_{SSV} = R_w \cdot \omega_{out} = \frac{\omega_{in}}{\frac{i}{R_w} \cdot R_w} \cdot R_w = \frac{785}{7{,}1} \cdot 0{,}04 = 4{,}44m/s$$

At this point we can know all the unknowns except for the mass:

$$k = \frac{v_{SSV}^2 \cdot m}{2 \cdot x \cdot T_{in}} \Rightarrow \mathrm{m} = \frac{k \cdot 2 \cdot x \cdot T_{in}}{v_{SSV}^2} = \frac{178 \cdot 2 \cdot 10 \cdot 6{,}36975 \cdot 10^{-3}}{4{,}44^2} = 1{,}53kg$$

The ideal mass of the SSV is 1,53 kg.

The only parameter that is unsure in these calculation is the gear ratio which is influenced by earlier the parameters mentioned 3.1.1. If the gear ratio decreases by 10%, the mass decreases with 23.5%; which is a lot. If a decrease in gear ratio off 3% results in a mass decrease off 8.5%. The conclusion is that the mass has to be round 1,5 kg, but to be safe, the SSV will be designed with a lower weight and during testing we can add some weight to determine the optimal mass of the SSV.

### 3.1.2. Ideal gear ratio (analytical)

The solar panel gathers energy from the sun and transforms it to electricity which provides power for the DC-motor. When a current is send trough the DC-motor, the rotor will start to turn. This rotor is connected to the drive shaft and this drive shaft has to be connected to the drive wheel. The shaft can't just be connected to the wheels because this would provide poor efficiency. That's why some gears will be used.

The right gear ratio and gears are selected to provide the SSV with a good speed and the right amount of torque. There are two possible directions to go with. The first one is to provide the SSV with a very large torque but with a smaller rotational speed. That's when the driven wheel is larger than the driving wheel, in Figure 14 represented as resp. driver and follower. This situation is called 'speed reduction'. It's also possible to have complete opposite, a smaller driven wheel than the driving wheel. This provides the SSV with a smaller torque but a larger rotational speed, this is called the 'speed boosting'.

So in paragraph chapter 3 the ideal gear ratio will be calculated in two ways.

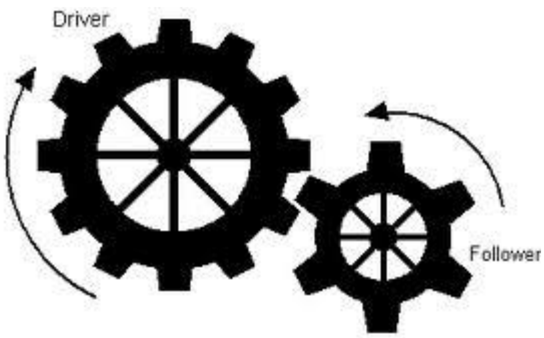



Figure 14: Representation of the gear ratio

We know that the gear ratio I $= \frac{w\ motor}{w\ wheel} = \frac{w\ motor * r\ wheel}{v\ wheel}$

In the calculations for the ideal mass we did find the formula:

$v_{SSV}^2 = \frac{2 \cdot x \cdot k \cdot T_{in}}{m}$ and we also know k * Tin = F and Pmax = v ssv * F

v ssv = $\sqrt[3]{\frac{2 * Pmax * x}{m}}$ with: Pmaxideal = 6.72 W , m = 1.53 kg , x=10m

v ssv = 4.44m/s = 16 km/h

w wheel = $\frac{v\ ssv}{r\ wheel}$ = $\frac{4.44}{0.04}$ = 111 rad/s

w motor, as calculated in the ideal mass calculations, is 785 rad/s

the optimal gear ratio is now: i= $\frac{w\ motor}{w\ wheel}$ = $\frac{785}{111} = 7.1$

(The results used during these calculations are calculated with the bisection method which is explained in chapter 3.4.)

For the sensitivity analysis, all the parameters that were found on external sources might not be completely accurate for this case. For the analytical gear ratio analysis these parameters are reduced by 10% and this shows the effect on the final ratio:

**Table 3: Table of sensitivity analysis**

| PARAMETER | EFFECT ON RATIO AFTER 10% DECREASE |
|---|---|
| The efficiency of the engine:n | 3,71% |
| Friction coefficient: Crr | 0,17% |
| Mass of the SSV: m | 3,00% |
| Air resistance: Cw | 0,69% |
| Air Surface: A | 0,69% |
| Gear loss | 1,12% |

Some of these numbers will affect the solution only very little, but some like the engine efficiency and gear loss have a big influence. The important parameters like engine efficiency and gear loss are very difficult to determine, but they have a big impact. Because of this, analytical calculating give a very good approximation but testing the SSV will still be very important.

### *3.1.3. Maximum height of the ball*

To determine the maximum height of the ball, the used speed and mass are the ones calculated analytically in 3.1.1 and 3.2.1. In our case it was 4.0256 m/s with a mass of 1.53 kg. The maximum height that can be reached is 1.02m in collision with the golf balls.

$$\frac{m \cdot v^2}{2} = m \cdot g \cdot h$$

$$\frac{1{,}53 \cdot 4{,}44\text{^}2}{2} = 0{,}735 \cdot 9{,}81 \cdot h$$

h=2.1m

With the collision a part of the energy is lost, the coefficient of restitution is 0.83.

$$Cr = \sqrt{\frac{v\ after}{v\ before}}$$

$$0{,}83 = \sqrt{\frac{v\ after}{4{,}44}}$$

v after =3.06m/s

$$\frac{1{,}5 \cdot 3.06\text{^}2}{2} = 0.7 * 9{,}81 * h$$

h=1.02m

### 3.2. Calculations in Matlab

Matlab can be used to solve the differential equation of our SSV. How the program works is explained in the last chapter. Here some code was added to find the optimal solution. The 'optimal solution' is defined as the maximum speed that the ball will have (after an ideal elastic collision). The result for the optimal solution is 1.4 kg as mass and 7.5 as ratio. The optimal values can also be found with a graph.

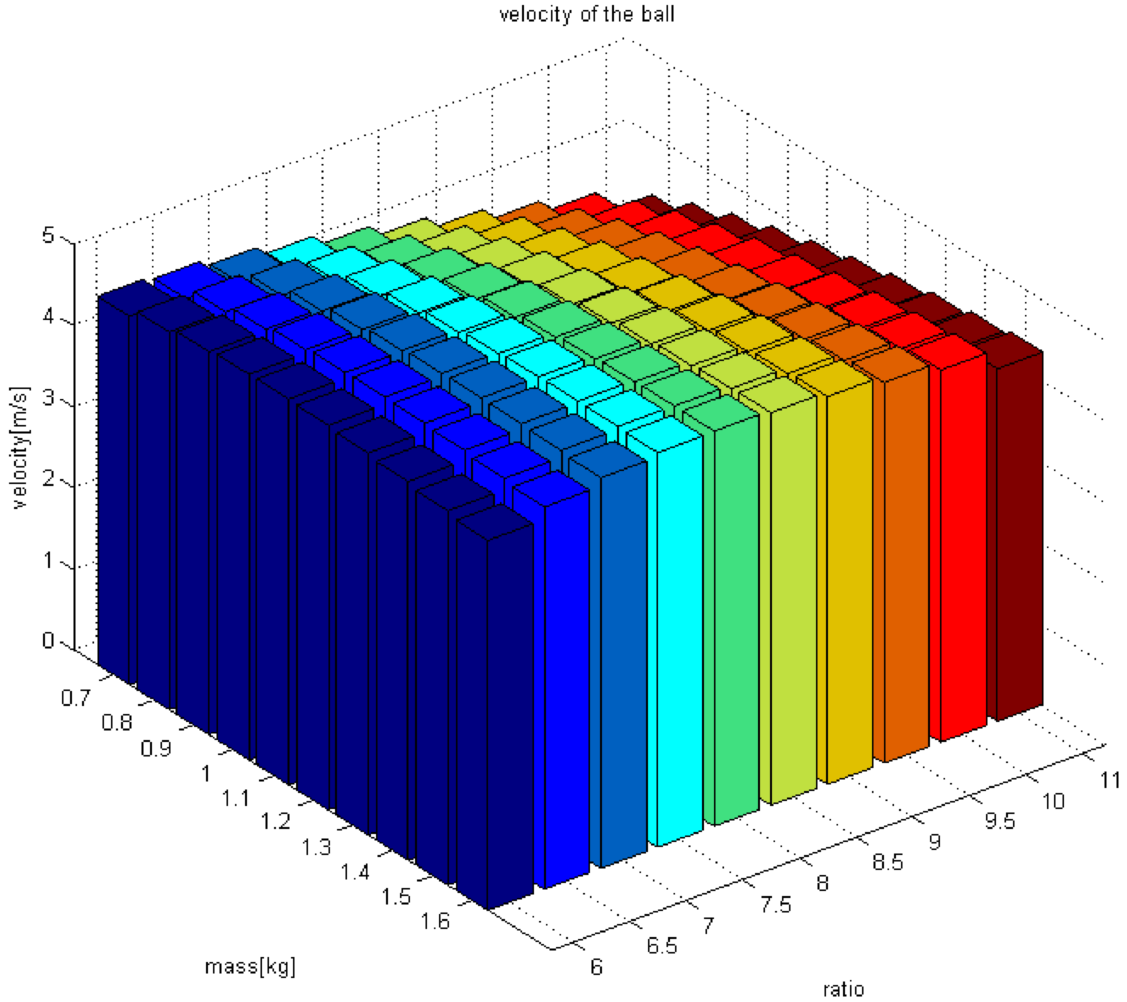



Figure 15: Bar3 plot of speedball matrix

#### 3.2.1. The ideal gear ratio and ideal mass in Matlab

The bar3 plot function of Matlab was used to plot all the values of the matrix speedball. It represents each number of the matrix by one bar (with the velocity as height). Only by sight it's possible to know that the optimal solution is somewhere around 1.4 kg and 7,5 as ratio. Most importantly this graph can be used to determine the influence of a different ratio or a different mass. For example a ratio of 6 is less influenced by the mass than a ratio of 9. This can be very useful later on. When testing the car, the parameters that can be changed without influencing the maximum velocity of the speedball too much, are known. From observation a list of the acceptable optimal solutions can be concluded: ratio = 7.5; 8; 8.5; 9 and mass = 1.1; 1.2; 1.3; 1.4.

The graph of the velocity and the position of the SSV is plotted with the optimal solution (m=1,4 kg and ratio 7,5).

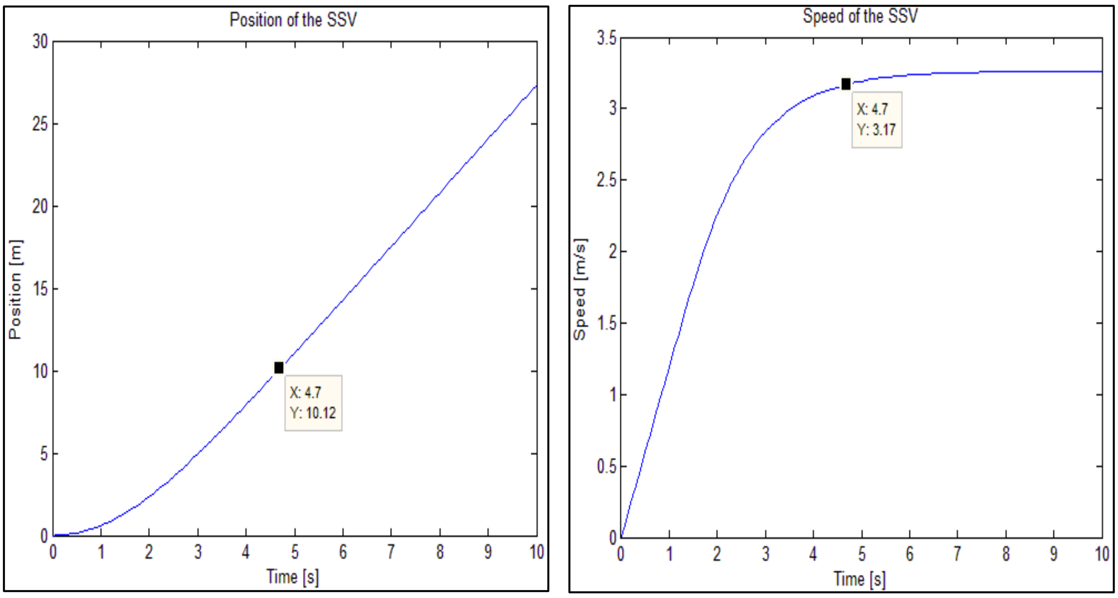



Figure 16: Position and speed of the SSV

First the analysis of the position graph is started beacause the travel time to determine the speed has to be determined. Matlab is working with certain time steps so it's not possible to get 10m right. At the moment the SSV will hit the ball, it will have travelled 4.7s and have a velocity of 3.17m/s. With this speed the velocity of the ball can be calculated( 4.88 m/s). It is this speed that will be used to calculate the height of the ball which will be 1.7m. The formula is explained in the case about Simulink.

### 3.2.2. The ideal ratio with position and speed graph and feasibility

Another way to analyze the optimal ratio is to plot all then 10 ratios with a mass of 1,4 kg and discuss the influence. This could have been done this with the mass but it won't be done because it has the same reasoning.

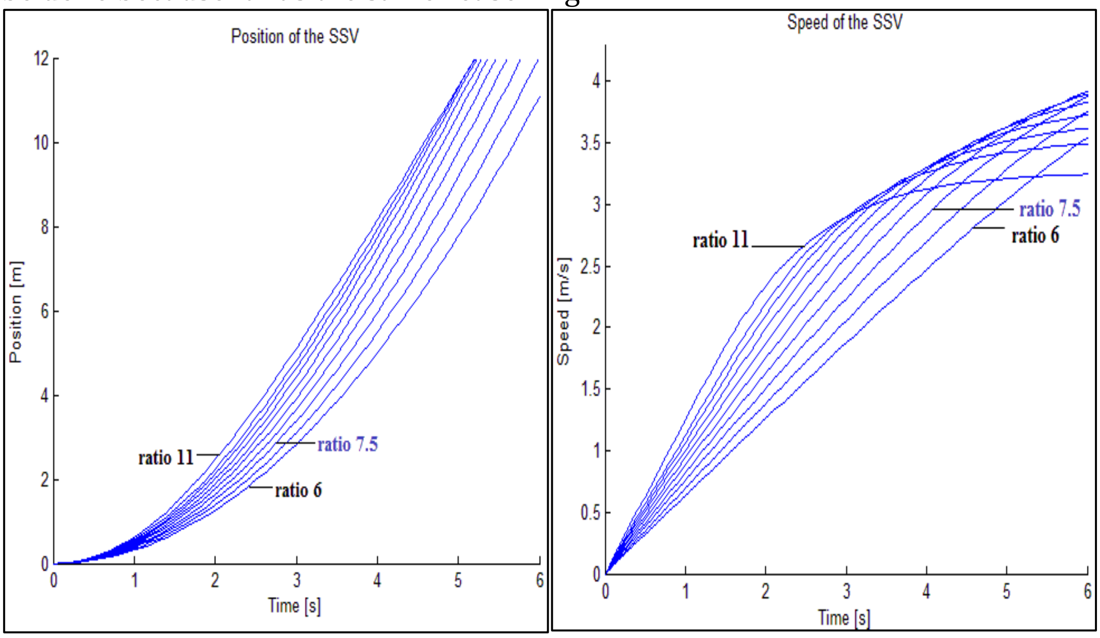



Figure 17: Position and speed of the SSV with various ratios

The best way is to draw a horizontal line at 10 m and see what the travel time is in the position graph. The travel time for each ratio is taken and as well as the velocity in the speed graph. The two graphs show that a ratio of 11 has less travel time but also less speed than the others. Travel time is not an important factor. The goal is to hit the ball at the highest speed and less travel time doesn't mean that the SSV has the highest velocity. This is because there is a long travel distance. Finally, it's possible to conclude that the optimal ratio of 7.5 is difficult to predict. Like the bar3 plot (velocity ball) it's possible to see that the velocities of other ratios are close to the optimal velocity.

## 3.3. Comparing Matlab with the analytical approach

After comparing both our results from Matlab and the analytical approach, it is possible to state that it is pretty much the same. This result was expected because Matlab is going to solve numerically what was done analytically. Even if the mass and the ratio slightly differ, it is possible to conclude that the set values were indeed the optimal solutions (see 3.2). The ideal ratio equals 7,5 but it could have been 7,8 because steps of 0,5 between each step were used. So as conclusion it's possible to take the ideal mass between 1,4 and 1,5 kg and the ideal gear ratio round 7,5.

For a gear ratio of 7.5, we are planning on using 3 gears (10, 25, 75 teeth). The gear ratio between each gear is calculated and then multiplied to have the final gear ratio.

The diameter of the gear is predictable by knowing its modulus and the number of teeth. The maximum diameter that we can have will be the gear with 75 teeth. We used a wiki page and looked in several stores to compare the several diameters. With a modulus of 0.5 the gear should have a diameter around 38.5mm. This is feasible for the SSV.

$$10 \xrightarrow{2.5} 25 \xrightarrow{3} 75$$

The final gear ratio will be: 2,5 x 3 = 7.5

### 3.4. Bisection method

The bisection method is actually an analytical way of predicting the behavior of the SSV. It is a numerical method by which both the displacement and speed curve for the first second during the race with time interval of 0.1s are determined. Therefore the analytically calculated gear ratio of 7,5 is used. When the calculating and drawing are done, these results must be compared with the results of Matlab.

The bisection method is generally used as a root finding method that repeatedly bisects an interval and then selects a subinterval in which a root must lie for further processing. If the root has to bigger than the average value of that selected interval, it lies in the right part otherwise in the left. By determining this, it is possible to make the intervals smaller and smaller until the right value is found. A representation of the bisection method can be seen in Figure 18.

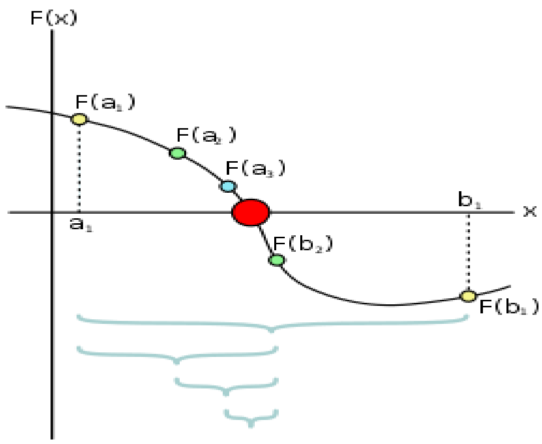



Figure 18: The bisectionmethod

#### 3.4.1. Brief example

To get familiar with the bisection method, a brief example will be solved:

$y = \frac{1}{2} + \sin\left(\frac{x}{2}\right) e^{\sin\left(\frac{x}{3}\right)}$ for X $\in[0,10]$

Search the y-values for the x-values in the interval.

y(0) = 0.5

y(10) = -0.29

The interval will become smaller and smaller now, but the zero point still needs to be within the interval.

The middle of the interval is 5.

y(5) = 2.12

The value is positive, the product of the two values around the null point has to be negative, otherwise the function wouldn't cut the x-as.

The smaller interval will be [5;10]. After doing this process several times you will become a very precise value.

| | | |
|---|---|---|
| X = 7.5 | f(7.5) = -0.54 | [5;7.5] |
| X = 6.25 | f(6.25) = 0.539 | [6.25;7.5] |
| X = 6.875 | f(6.875) = -0.118 | [6.25;6,875] |
| X = 6.563 | f(6.563) = 0.184 | [6,563;6,875] |
| X = 6.719 | f(6.719) = 0.026 | [6,719;6,875] |
| X = 6.797 | f(6.797) = -0.048 | [6,719;6,797] |
| X = 6.758 | f(6.758) = -0.0114 | [6,719;6,758] |
| X = 6.739 | f(6.739) = 0.007 | [6,739;6,758] |

**X = 6,74**

So in this case 6.74 is the root.

### 3.4.2. Bisection method for the SSV

In the following section the bisection method will be performed for the SSV.

#### *3.4.2.1. Calculation forces*

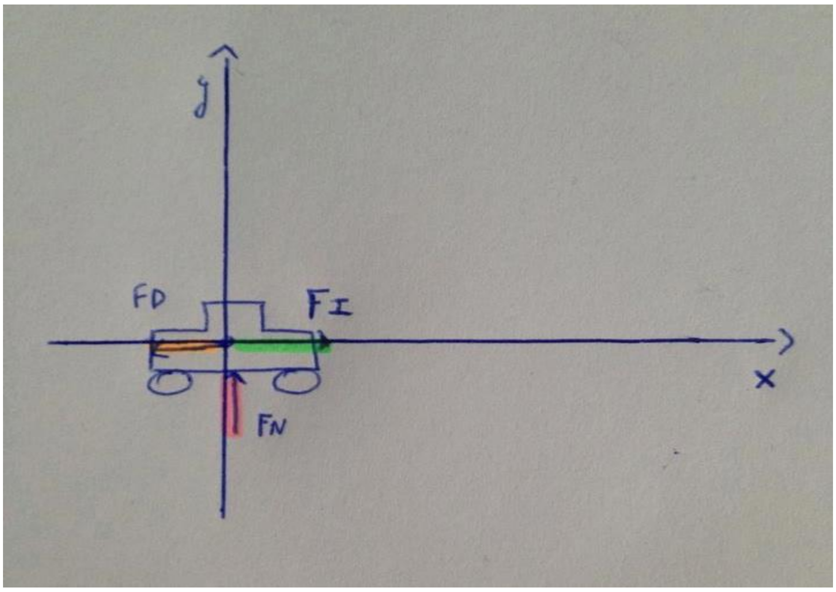



Figure 19: Forces on the SSV

Air resistance $F_D = -Cw \times A \times \frac{v(t)^2}{2}$

Motor force $F_I = E(t) \times \frac{I(t)}{v(t)}$

Normal force $F_N = m \; g$

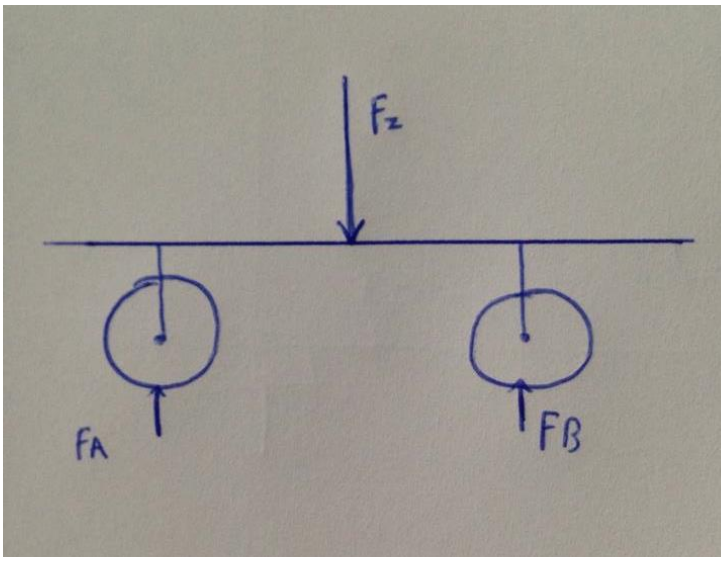


Figure 20: Forces on the wheels

The gravity is evenly distributed between the wheels, which means that Fa and Fb are equal. The ideal mass of the car is about 1400 g.

Fz = 13,734N
Fa = Fb = 6,865N

## Motor

$$E(t) = \frac{Ce \cdot \Phi \cdot 60 \cdot v(t) \cdot gear\ ratio}{2\pi r}$$

## Solar panel

$$I(t) = Isc - Is\left(e^{\frac{E(t)+I(t)\cdot R}{M \cdot N \cdot Ur}} - 1\right)$$

The acceleration can be found by Applying The second law of Newton.

$$a(t) = -\frac{Fa}{m} \cdot Crr - \frac{Fb}{m} \cdot Crr = \frac{Ce \cdot \Phi \cdot 60\ v(t) \cdot gear\ ratio}{2\pi r} \cdot \frac{I(t)}{M \cdot v(t)}$$

$$- \quad \frac{Cw \cdot A \cdot rho \cdot v(t)^2)}{2 \cdot M} \quad (1)$$

Parameters :

- Solar panel

Isc – short circuit current = 1.03 A
Is – saturation current = 1e-8 A
Ur – thermal voltage = 0.0257 V at 25° C
m – Diode factor = 1.08 dimensionless
N – Number of solar cells in series = 16 dimensionless
DC-motor
R – Terminal resistance = 3.36 Ω
Ce – Inverse of the speed constant = 8.93e-4 V/rpm
Air resistance
Cw – Drag coefficient = 0.5 dimensionless
A – Frontal surface area = 0.03 $m^2$
Rho – Density of air = 1.290 $kg/m^3$
Rolling resistance
g – gravitational constant = 9.81 N/kg
Crr – rolling resistance coefficient = 0,012 dimensionless

- SSV

r – wheel radius = 0.04 m
Gear ratio = 7,5

These parameters are necessary in order to make appropriate calculations.

### *3.4.2.2. Calculations time interval [0;0,1]*

The initial conditions are:

x(0) = 0; v(0) =0; I(0) = 1,03 A

The acceleration can be found by filling in all parameters in equation (1)

a(0) = -2· (3,6/1,47) · 0,012+((8,93E-4·60·6,5)/(2·3,14·0,04)) · (1,03/1,47)-(0,5·0,03·1290·0)/(2·1,47)

a(0) = 0,913 $m/s^2$

Initial conditions for the next interval

V(0,1) = v(0) + a(O) · T = 0,0913 m/s

X(0,1) = X(0) + v(0)T+a(0) $\cdot \frac{T^2}{2}$ = 0,004565 m

E(0,1) = $\frac{Ce \cdot \Phi \cdot 60 \cdot 0{,}0913 \cdot gear\ ratio}{2\pi r}$ = 0.126 V

Bisection method (1)

**T = [0;0,1]**

$$y = 0 = Isc - Is\left(e^{\frac{E(0.1)+I(0.1)\times R}{M\times N\times U_T}} - 1\right) - I(0.1) \quad x = I(t)\ en\ y(x) = y(I(t))$$

x ∈[1;1,1] met y(1) = 0,3; y(1,1) = -0,07

| | | |
|---|---|---|
| x = 1,05 | y(1,05) = -0,47 | [1;1,05] |
| x = 1,025 | y(1,025) = 0,0049 | [1,025;1,05] |
| x = 1,0375 | y(1,0375) = -0,0075 | [1,025;1,0375] |
| x = 1,0125 | y(1,0125) = 0,00126 | [1,0;1,0125] |

X = 1,0125

I(0,1) = 1,0125

### *3.4.2.3. Calculations time interval [0,1;0,2]*

The initial conditions are:

x(0,1) = 0,004565; v(0,1) = 0,0913; I(0,1) = 1,0125

The acceleration can be found by filling in all parameters in equation (1)

a(0,2) = -2· (3,6/1,47) ·0,012+((8,93E-4·60·6,5)/(2·3,14·O,04)) · (1,0125/1,47)-(0,5·0,03·1.290·0,0913^2)/(2·1,47)

a(0,2) = 0,913 $m/s^2$

Initial conditions for the next interval

V(0,2) = v(0,1) + a(0,1) ·T = 0,27 m/s

X(0,2) = X(0,1) + v(0,1)T+a(0,1)· $\frac{T^2}{2}$ = 0,004898 m

E(0,2) = $\frac{Ce \cdot \Phi \cdot 60 \cdot 0{,}27 \cdot gear\ ratio}{2\pi r}$ = 0,37v

Bisection method (2)

**T = [0,1;0,2]**

$$y = 0 = Isc - Is\left(e^{\frac{E(0.2)+I(0.2)\times R}{M\times N\times U_T}} - 1\right) - I(0.2) \quad x = I(t) \text{ en } y(x) = y(I(t))$$

x

∈[1;1,1] met y(1) = 0,3; y(1,1) = -0,07

| | | |
|---|---|---|
| x = 1,05 | y(1,05) = -0,02 | [1;1,05] |
| x = 1,025 | y(1,025) = 0,0049 | [1,025;1,05] |
| x = 1,0375 | y(1,0375) = -0,0075 | [1,025;1,0375] |
| x = 1,0125 | y(1,03125) = 0,00127 | [1,0;1,025] |

X = 1,0125

I(0,2) = 1,0125

The same calculations were made to get following table.

**Table 4: Results bisection method**

| T [s] | a(t) [m/s^2] | v(t) [m/s] | x(t) [m] | E(t) [a] |
|---|---|---|---|---|
| 0,0 | 0,913 | 0,0 | 0,0 | 0,0 |
| 0,1 | 0,913 | 0,091 | 0,0045 | 0,126 |
| 0,2 | 0,913 | 0,270 | 0,0048 | 0,370 |
| 0,3 | 0,926 | 0,312 | 0,0540 | 0,432 |
| 0,4 | 0,927 | 0,415 | 0,1760 | 0,574 |
| 0,5 | 0,924 | 0,520 | 0,3740 | 0,720 |
| 0,6 | 0,920 | 0,615 | 0,6980 | 0,852 |
| 0,7 | 0,919 | 0,709 | 1,1768 | 0,983 |
| 0,8 | 0,917 | 0,799 | 1,8330 | 1,102 |
| 0,9 | 0,914 | 0,870 | 2,6960 | 1,206 |
| 1,0 | 0,914 | 0,977 | 3,7900 | 1,354 |

These results are plotted in following graphs. Figure 21 shows a linear gradient, which is correct. The function of speed is a straight line.

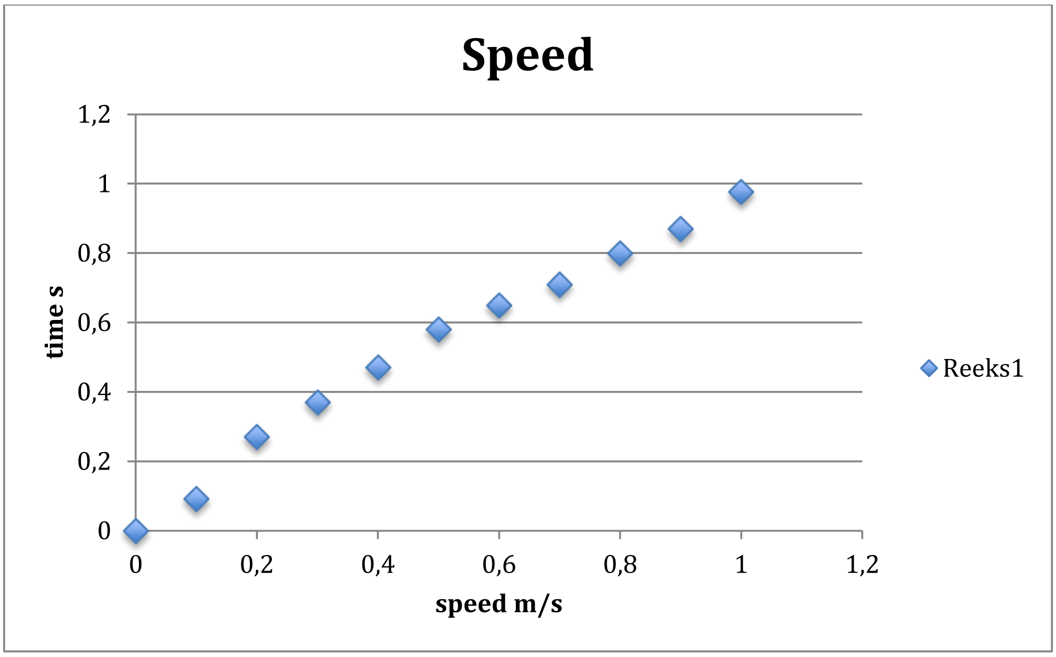


Figure 21: Speed graph constructed with bisection method

The distance graph (Figure 22) is parabolic, if this graph is compared with the graph of Simulink (see other report: Simulink) it's possible to conclude that both graphs are equal. The distance in the beginning is very small, because the speed is low and the time interval is also negligible.

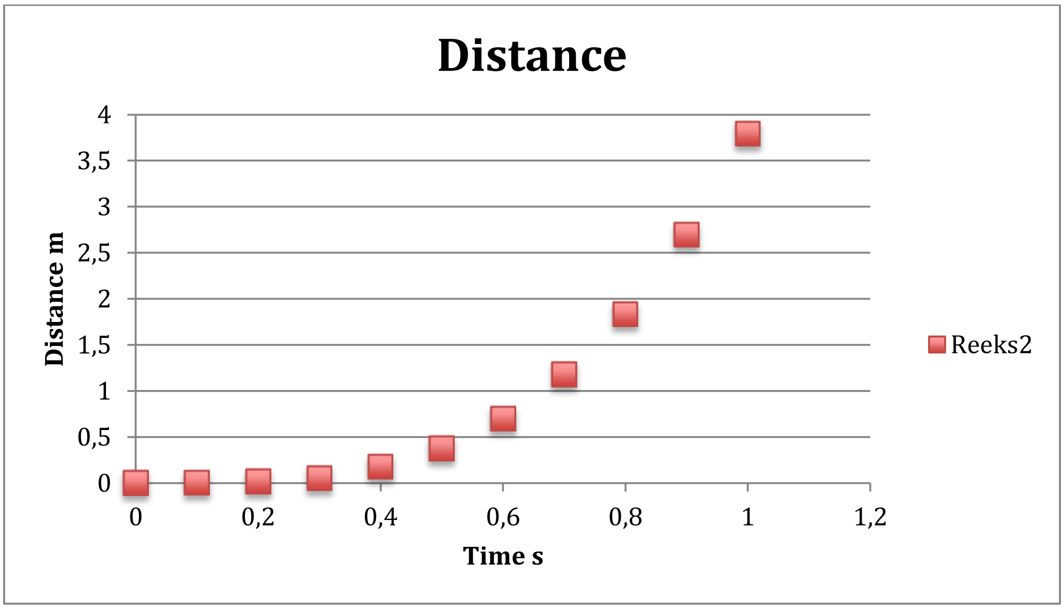
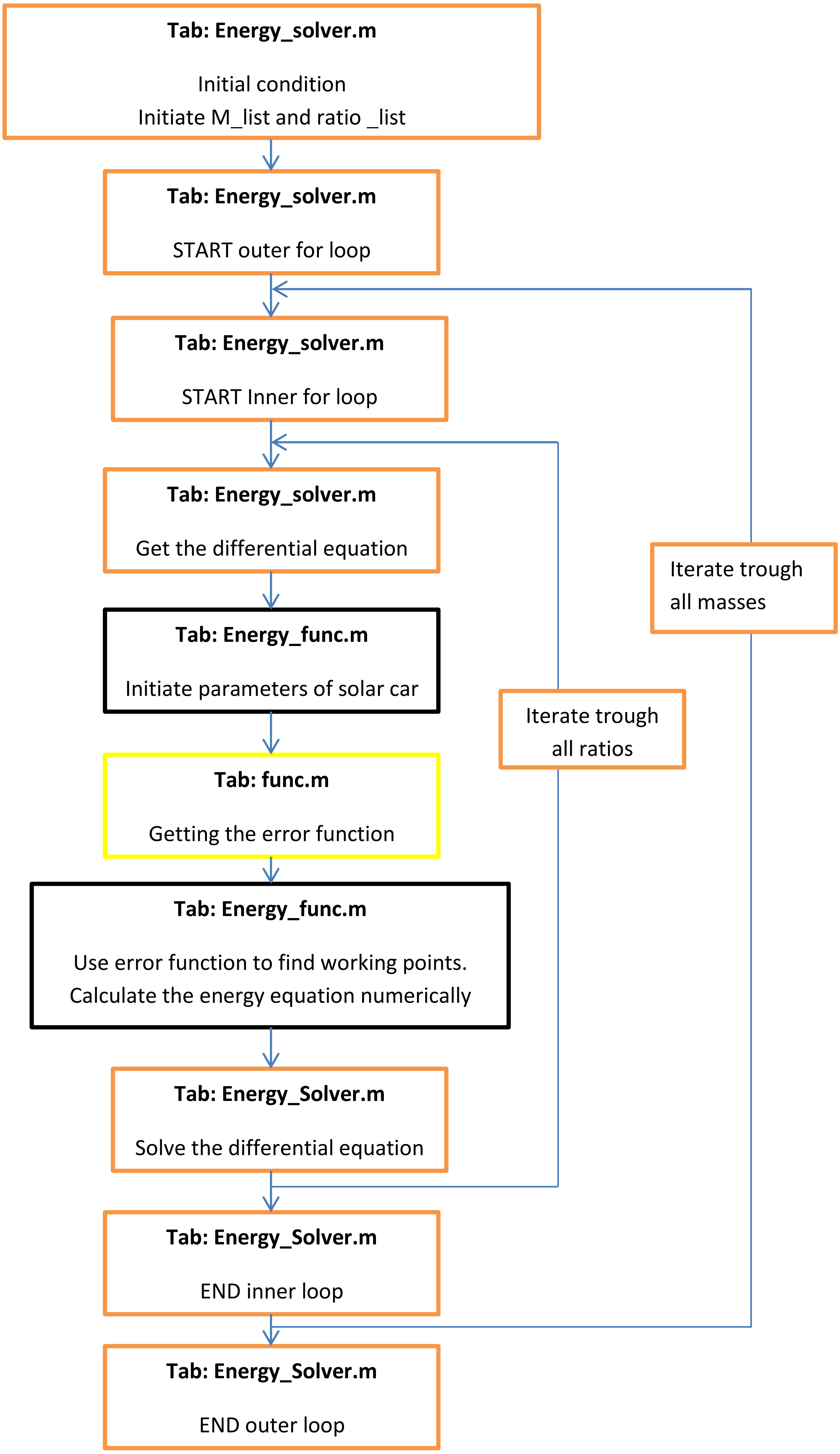


Figure 22: Distance graph constructed with bisection method

It's possible to conclude that the information can be found by calculating them by hand, but simulink and Matlab are more precise. If new parameters have to be set, all calculations have to be done again. With the computer it's not necessary, it's less work to get the results with new parameters.

## 4. Matlab extra questions

A)Energy_solver.m uses Energy_func .m and Energy_func uses func.m.



## B) Explain the following line in your own words. What are t and s?

Ode15s is a function in Matlab to solve Ordinary Differential Equations (in our case the energy equation in the page Energy_func.m).
t is a vector with the time points
s is a solution array. It contains the corresponding speed and position to a particular time.

```
            index=find(s(:,1)>=10,1);
            speed(i,j) = s(index-1,2)+(s(index,2)-s(index-1,2))*(10-s(index-1,1))/(s(index,1)-s(index-1,1));
            speedball(i,j) =  (2*M*speed(i,j))/(M + M_ball)
        end
    end
    [opt1,index_mass]= max(speedball)
    [opt2,index_ratio]=max(opt1)
    ratio = ratio_list(index_ratio)
    mass = M_list(index_mass(index_ratio))
    hoogte_ball = (opt2*7*opt2)/(10*9.81)
```

Figure 23: Code Matlab Energy_Solver.m

## C) What is done here and why?

The first line of code is going through the results of the energy equation and gets all the indices of those with a position less than 10,1m. This is normal because our track has a length of 10m. We don't need the positions above 10m.
The second line calculates the speed of a certain mass and ratio. It puts the speed in a matrix [mass = i, ratio = j]. This is useful to calculate the speed of the ball at each ratio and mass. We've put that in a matrix with the same index as the speed matrix.
The part after the for-loop determines the optimal ratio and optimal mass. It gets the highest number in the matrix speedball and gives the corresponding index of the mass and ratio.
The only thing left to do is to get the optimal ratio and mass.
The height of the ball is calculated with formula that is explained in the Simulink chapter.

## D) What is the function of this file?

In the first part we can choose the parameters of our DC-motor, solar panel, air resistance, rolling resistance and wheel radius. The second part solves the energy function numerically.

## E) What are dx, t and x? Why are they in this line? Does there exact name matter for the program?

dx means the derivate of the position, dx is the name used for velocity. x is the position, t is the time. Their exact name doesn't matter if you're consequent. It is better not to use a parameter name that has already been used. In the Energy_solver we use for position s and in Energy_func we use something different x. The reason here is to not lead yourself and the program into confusion. If we use the same in 2 functions this value can be changed by those two functions and thereby we can't follow the change of the variable.

## F) Does the exact name of these parameters matter? Why (not)?

No, you need to be consequent. In general you can use the official symbol for a better understanding by other people. If you change a name, you will have to use the same name each time you want to use it. Matlab doesn't know the symbols Isc or Ur. I can call it a and b if I want. It's the user that defines them.

G) For the parameters see the section 'Calculation key components'.

H) What is x(2)?

x(2) is the velocity in function of the time.

$E(t) = Ke \times \omega = CE.\Phi \times 60 \times v(t) \times \text{gear ratio} /(2\pi r)$

I) What is TolFun? What is fzero and why do we call it here? What are sol and f?

TolFun is the termination tolerance on the function value. When the function value is a number less than the chosen one (1e-15), the action stops. This allows being more efficient in solving the equation (loose less time). fzero looks for the root of the function func and an additional parameter x(2) is added(because of the velocity). When the function func is equal to zero you have 2 unknown parameters, the voltage and the velocity. The fzero is going to put the results in an array with Sol as the working point(voltage) and f which is zero. Sol is then used to know if the voltage is in the range of the solar panel and calculate the current to the motor.

```
options=optimset('TolFun',1e-15);
[sol,f]= fzero('func',0,options,x(2));

U=sol;
if U>9
    I=0;
else
    I=Isc-Is*(exp(U/(m*N*Ur))-1);
end
E = 60*Ce*x(2)*ratio/(2*pi*r);

dx=zeros(2,1);
dx(1)=x(2);

if x(2)==0
    dx(2) = -Crr*g + 60*Ce*ratio/(2*pi*r)*I/M ; % energy equation
else
    dx(2) = -Crr*g + (E*I)/(M*x(2)) - Cw*A*rho*x(2)*x(2)/(2*M) ; % energy equation
end
```

**Figure 24: Code Matlab Energy_func.m**

J) Explain the energy equations. What is the difference?

dx is an array with two colons and one row = [x(1)=velocity; x(2)= acceleration]. So, x(2) is the acceleration. The if-function was not necessary but it divides the analysis of the formula in two cases. If x(2)=0(the velocity is at the start zero) then the formula for the acceleration is simplified because the last term is also zero(the air resistance goes away). In the other case the velocity is not zero. We need to use the entire formula for the acceleration.

## K) What is the function of this file. How is it used?

This sheet contains the error function. To calculate the error with precision we need to take the back EMF of the motor into account. But the DC-motor has an inner resistance and that causes losses (= voltage drop). If we take these two we have the error on a chosen voltage(with the according velocity). This sheet is used in Energy_func to find the working point of the solar panel and the DC-motor at a specific velocity.

## L) What is f?

f is the error expressed in Voltage

f = voltage (variable) – voltage drop (inner resistance motor) – back EMF DC-motor

# Conclusion

This was the first part of the small solar vehicle. The first part consists of establishing the behavior of SSV during the race. Therefore a lot of key components had to be determined. This was done in an analytical way as well as in a simulation. The most important components that had to be determined were: ideal gear ratio and ideal mass. But to determine these two values a lot of other components had to be determined.

After determining all the different components it possible to state the final values for the most important components. The ideal gear ratio is between 7,5 and 8. With the analytical method the result was 7,8 and with the simulation the result was 8. When building the SSV different gear ratios can be used to determine the ideal value.

The ideal mass was also determined in two ways. Both the method predict an ideal value round 1,4 kg. It's better to build a lighter car because it's easier to gain weight than lose weight.

This project continues in the second report Simulink where the behavior of the SSV will be tested in the real race situation.

After that part the build of the car will start. Before the big race, the car will first be tested in a real life tests.

# List of literature

The literature used to finish this case can be found on Toledo. The slides from the seminar and other presentations as well as the different data sheets were used to complete this case.

Other useful literature:

The engineering Toolbox (sd.) *Rolling resistance* from:
http://www.engineeringtoolbox.com/rolling-friction-resistance-d_1303.html

Delta Wing projects (2013) *The Car* from: http://www.deltawingracing.com/the-car/

How stuff works (2000) *How gear ratio work* from:
http://science.howstuffworks.com/transport/engines-equipment/gear-ratio.htm

Golf club technology (2009) *coefficient of restitution* from:
http://www.golfclub-technology.com/coefficient-of-restitution.html

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# SSV Case Simulink

WEIGHT LIGHT

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23 May 2014

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Building a small solar vehicle

Lightweight

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23 May 2014

# Table of content

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# Introduction

The general idea of this report is to determine the optimal mass and gear ratio of our solar vehicle. To generate these values, we used Matlab and Simulink. These are some mathematical programs to help with an analytical analysis. Before determining the optimal parameters, some other simulations were done. With these simulations a better view of the behavior of our SSV is created. However in race situations these values won't be the same but the general idea of what to expect is present.

# 1. Behavior of the solar panel

## 1.1 Matlab simulation

The first case is a simulation of the behavior of our solar panel when different values of loads are connected. Firstly the maximum power that the solar panel could deliver has to be determined. The loads vary from 0 to 100 [ohm]. In the beginning a lot of resistor values were taken (figure 1). This point is a crucial section.

```
% replace these values for the resistance with relevant values
R_list=[1 2 3 4 5 6 6.25 6.5 6.75 7 7.25 7.5 7.75 8 8.25 8.5 8.75 9 10 11 12 13 14  15 16 17 18 19 20 25 30 35 40 50 60 65 70 75 80 85 90 95 100]
```

*Figure 25: Resistor values*

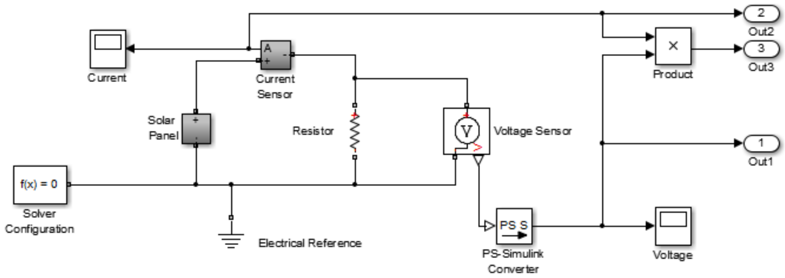



**Figure 26: Solar panel with resistor**

For each resistor value, Matlab determines the corresponding current and voltage those are the outputs out1 (current) and out2 (voltage). This is also what is visible in figure 3.

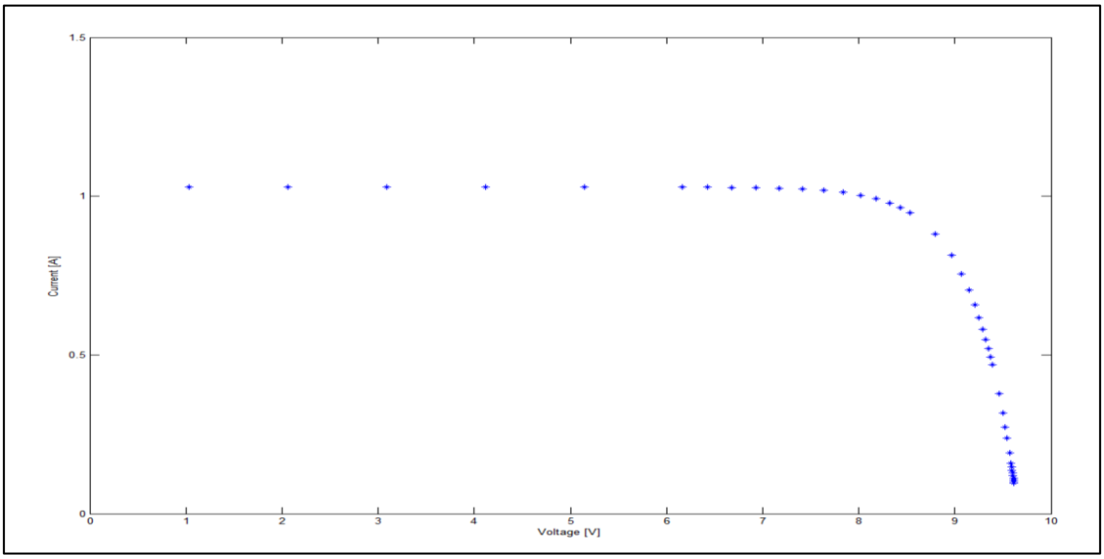



**Figure 27: Current-Voltage relation**

Now that the current and voltage have been determined, Matlab can use the Simulink model to calculate the maximum power by multiplying the current with the voltage, then store in a matrix. This allows us to find the maximum value in that matrix and find the corresponding resistance. The result was a maximum power value of 8.137 [Watt] with a resistor of 8.5 [Ohm]. Figure 4 shows the maximum point on the power graph.

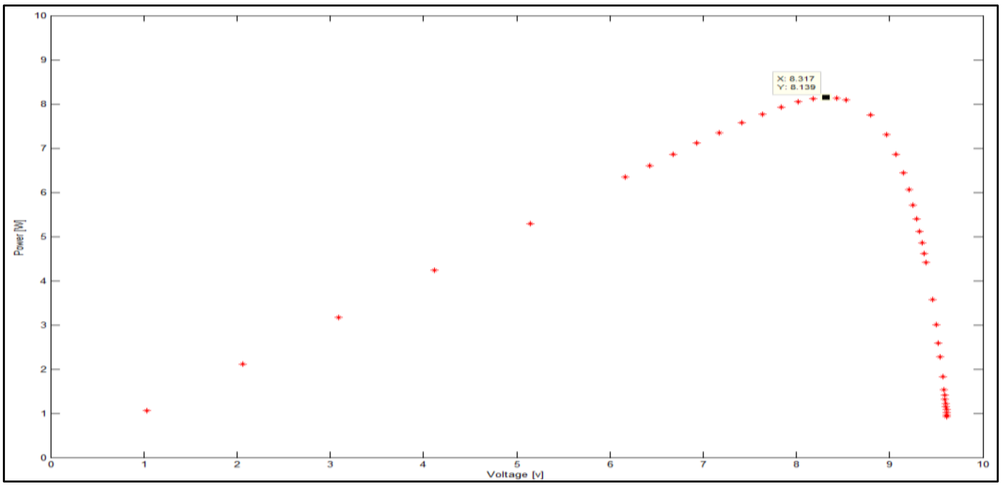



**Figure 28: Power Graph**

## 1.2 Measurements

At the beginning of the project, the max power was determined. This was in a laboratory using a bright lamp. For the measurements the max power is 4.28 Watt (Figure 10).

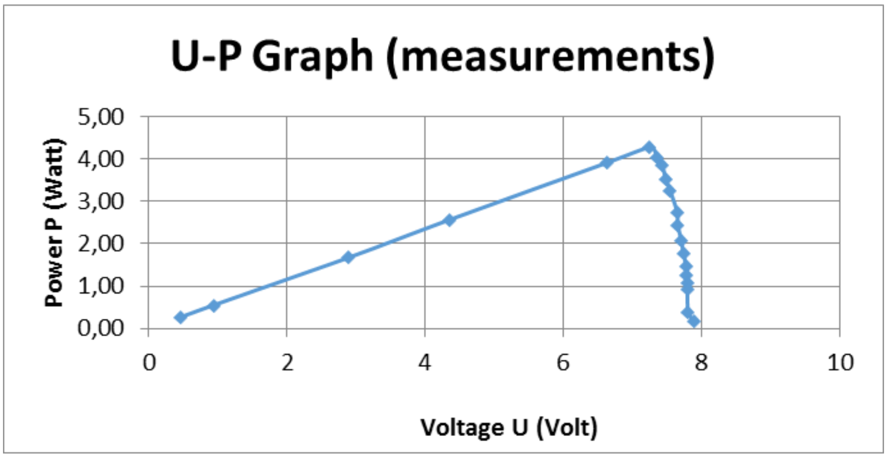



*Figure 29: U-P Graph (measurements)*

## 1.3 Conclusion

Both the graphs contain some ‘errors’ so to determine the max power it’s necessary to discuss them both. The measurements were done under a bright lamp but the SSV will be powered by the sun so the real maximum power will be slightly higher. For the ideal solar panel the Isc (Short-circuit current) was used as written in the data sheet of the solar panel: 1.03 Ampère. In our Matlab calculations, a Shot-circuit current of 0.9 Ampère was used. The ideal solar panel is near the maximum power but the measured power isn’t. This is because we used 0.59 as Isc and that is almost the half (of 0.9) so that explains also why we measured half the maximum power

# 2. SSV without solar panel

The goal of this case is to calculate the total distance the SSV will travel when the solar panel is disconnected. To calculate this distance a little trick is applied.

First the speed of the ball is calculated it will have when it starts rolling from a slope with a height of 1 meter. In the begin situation, there's only potential energy, because of the height. When the ball starts rolling the potential energy is transferred to kinetic energy. When the ball descends 1 meter, all the potential energy is transferred to kinetic energy. This principle is also known as the conservation of energy.

## Situation 1: the ball is at rest at a height of 1 meter

So at this situation there is only potential energy. The potential energy could be calculated with this formula:

$\mathbf{E_{pot}} = \mathbf{mgh}$ =7.21 [J]

<u>With the follow parameters:</u>

m : the mass of the ball: 0.735 [kg]

g : the gravitational constant: 9.81 [$m^2/kg^2$]

h: the height: 1 [m]

## Situation 2: the ball has descend 1 meter

So at this situation the potential energy has transformed into linear and rotational kinetic energy (figure 6). To calculate the rotational energy, the inertia moment has to be calculated. So for calculations, this equation is used:

$$\mathbf{E_{kin}} = \frac{\mathbf{mv^2}}{\mathbf{2}} + \frac{\mathbf{I\omega^2}}{\mathbf{2}}$$

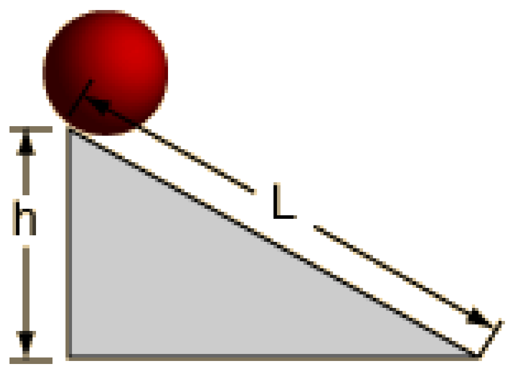



Figure 30: slope with ball

<u>With the following parameters:</u>

I= $\frac{2mr^2}{5}$ [kg*m²]

m: the mass of the ball = 0.735 [kg]

v: the velocity [m/s²]

In this equation the velocity is the missing parameter. So it's not possible to solve this equation separately. This is possible with the conservation of energy.

$$\mathbf{E_{pot}} = \mathbf{E_{kin}}$$

$$mgh = \frac{1}{2} \cdot mv^2 + \frac{1}{2} \cdot \left(\frac{2}{5} \cdot m \cdot r^2\right) \cdot \left(\frac{v}{r}\right)^2$$

If we solve this equation for v, we find

$$v = \frac{1}{7} \cdot \sqrt{70} \cdot \sqrt{gh}$$

Using the equation above, the velocity of the ball, after descending 1 meter, can be calculated.

$$\mathrm{v} = \sqrt{\frac{10}{7}\mathrm{gh}}$$

$$\mathrm{v} = 3.74\ [\frac{\mathrm{m}}{\mathrm{s}^2}]$$

So when you take a closer look at the equation, there's a little remark. The mass of the ball doesn't come back in the equation.

So the ball will hit our car with a speed of 3.74 [m/s²]. A little trick was used to simulate this in Simulink. The normal circuit is used (see figure 7), but with a switch within it. When the SSV has traveled 8.45 meters, the switch will disconnect the solar panel. At this distance the velocity of the SSV will be 3.74[m/s²]. From now on the motor will run without the solar panel. No power is delivered to the motor, so at a certain moment the SSV will stop.

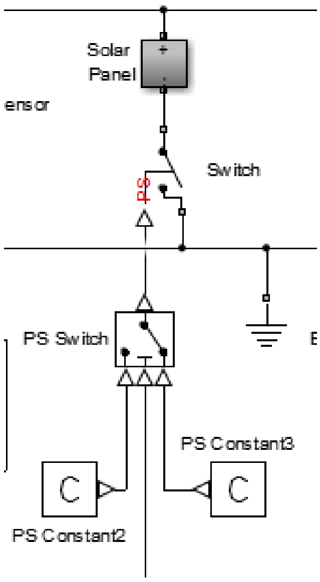



Figure 31 : Switch reverse race

The switch could also be connected to the velocity output of the Ideal Translational Motion Sensor. When the velocity reaches 3.74 [m/s²] the switch will disconnect the solar panel. This is another approach. The PS-switch is used to control the real switch. It checks if the chosen threshold (position) has been exceeded or not. It then sends one the PS constant and it's those PS constant that will determine if the switch is closed or not

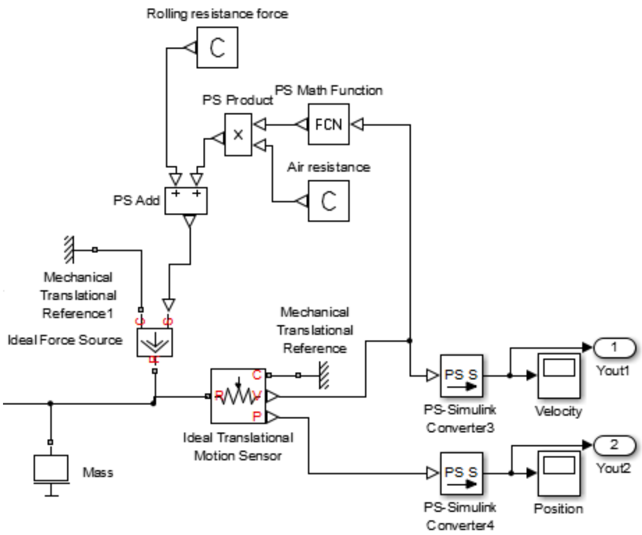



Figure 32 Loads for the ideal Force Source

To have a realistic simulation we had to add the loads to the Simulink model. Those are the air resistance and the rolling resistance. The velocity is connected to a PS math function which is going to take the square of the velocity. It's needed to calculate the air resistance.

So in the Figure 33 it is possible to see that when the velocity reaches 3.744 [m/s²], the solar panel is disconnected and the motor will get no power supply. The speed will decrease and after 25.461 seconds the speed will be zero. When an analytical approach is performed, the SSV will reach faster the speed of 3.744 [m/s²]. In an analytical approach losses caused by rolling and air resistance aren't taken in count.

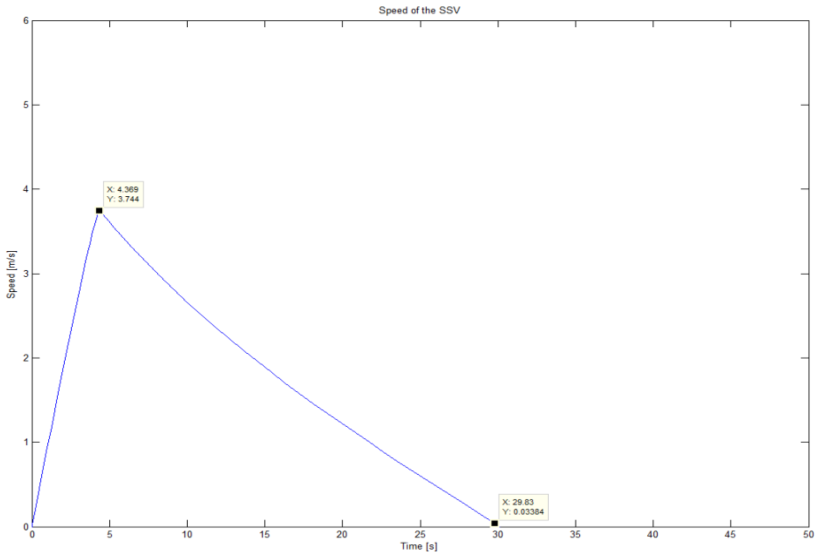



Figure 33: Speed of the SSV

Now when looking at the position graph ( Figure 34) where the position of the SSV is displayed at 29.83 seconds and looking at figure 2, you can see that the SSV has traveled a distance of 51.7 meters. But this is total distance, only the distance it will travel after the solar panel is disconnected is needed.

$$51.7 - 8.45 = 43.25 \text{ [m]}$$

The graph has the shape of a parabola with the top in 51.7 (Y-coordinate). After is has reached this value the graph will descend. This is impossible for the SSV, because this means that the SSV will ride backwards.

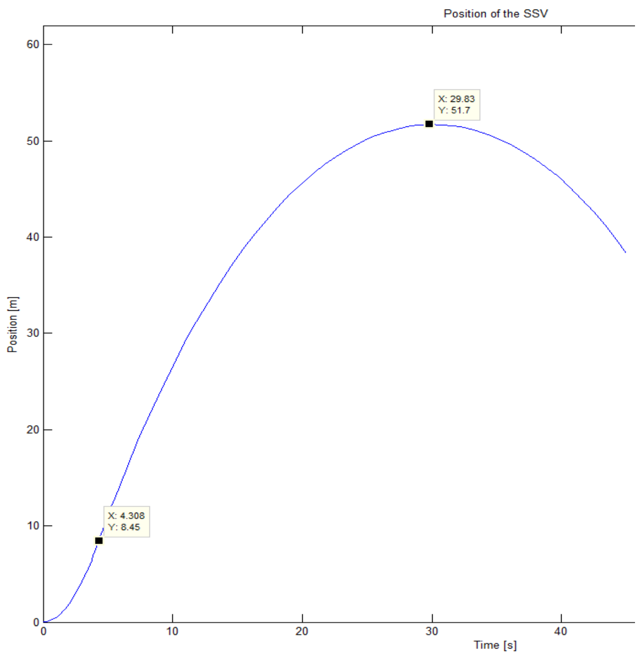



Figure 34: Position of the SSV

# 3. The real race simulation

Now a real simulation of the race is performed, the solar panel is connected with the DC-motor. The goal of this simulation is to determine the optimal gear ratio and the optimal mass of our SSV.

For this simulation the same circuit as in the attachment is taken, the only difference is that in this simulation no switch is used.

To find the optimal mass and gear ratio, a lot of different values for the mass and the gear ratio are entered in the program (figure 11). Matlab will simulate this and give the optimal combination.

```
M_list = [0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6] ; % kg
ratio_list = [6 6.5 7 7.5 8 8.5 9 9.5 10 11];%
```

Figure 35: Mass - Ratio:

The optimal mass of our SSV will be 1.4 [kg] with a gear ratio of 8.5. When these parameters are taken into account, the expected height of the ball will be 1.75 meters.

The following figures will give you a better interpretation of our SSV during the race. They show the speed and the position of our vehicle. Of course these calculations are based on approximations. The conditions during the race will never be the same but it gives us a good idea.

It will take +- 4.5 seconds to travel the 10 meters (figure 11), in the other graph you see that our vehicle will have a final speed of 3.5 [m/s²].

<u>Remark:</u>

We also have to give some graphs based on the mass and gear ratio. For this graphs, please look in our other report (Case SSV 1). It has already been made for the Matlab case. The reasoning is the same.

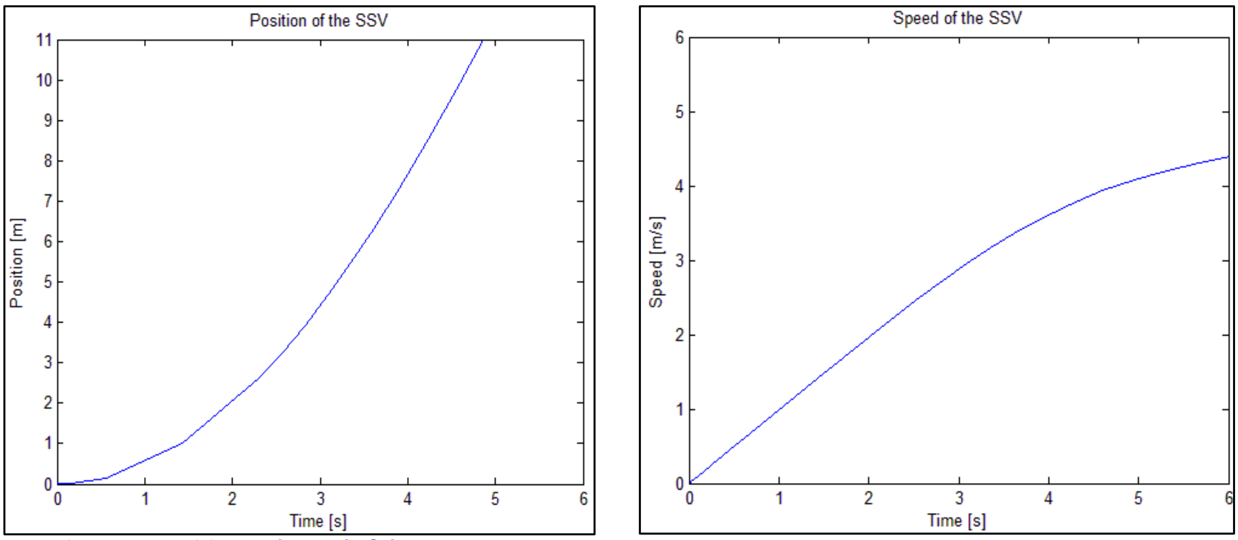



Figure 36: Position and Speed of the SSV

# 4. A deeper look at the simulations

Before a design it is very useful to know how your object, in our case the SSV, will react. Matlab and Simulink are very useful to get this information. Matlab and Simulink make these difficult calculations very easy and fast. With the plots the behavior of the SSV can be determined immediately.  This is much more difficult with an analytical approach. When 1 parameter is changed, the calculations have to do be done all over again.

# 5. Attatchments:

´

## 5.1 Parameters for the Simulink simulation

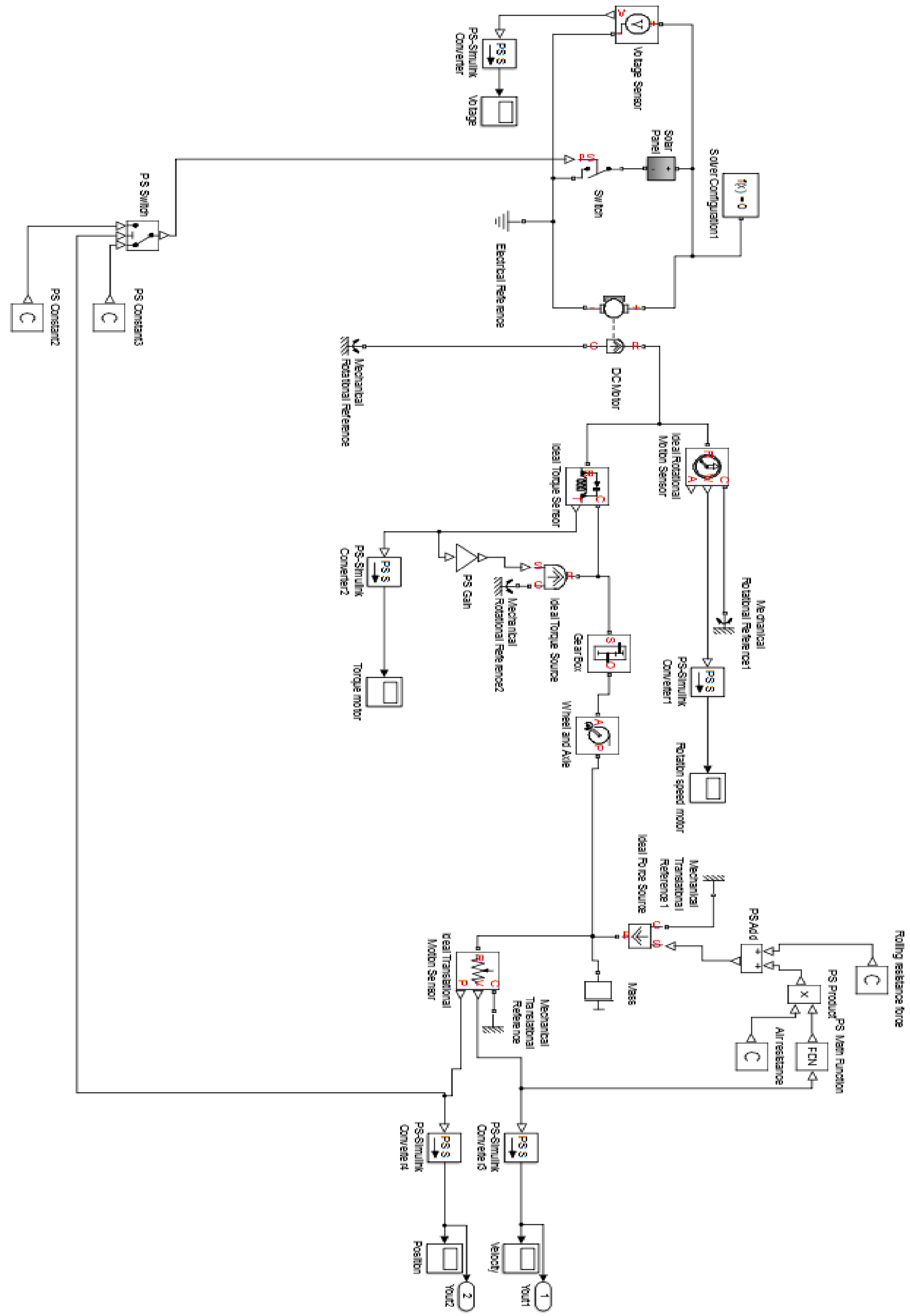
```
%%% Solar Power
Ir = 800;   % solar irradiance [W/m^2]
Is = 1e-8; %A/m²
Isc = 0.9;  % short circuit current [A]
Voc = 9.6;  % Open circuit voltage [V]
Ir0 = 700;  % irradiance used for measurements [W/m^2]
m = 17.28;    % diode quality factor

%%% Motor parameters
Ra = 3.36;
Km = 1/1120; %V/rpm
L  = 0.222; %mH
Cm = 8.93e-4;

%%% Gearbox
efficiency = -0.25;

%%% SSV parameter
Cw  = 0.5;
A   = 0.03;
rho = 1.290;
Crr = 0.012;
g   = 9.81;
%%% Wheel radius
r = 0.04;
```

## 5.2 Simulink model



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# SSV Case II

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23 May 2014

INTERNATIONALE HOGESCHOOL LEUVEN

# SSV Case II

Building a small solar vehicle
Lightweight

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23 May 2014

# Foreword

After a lot of hard work and having met several times a week, the first part of our small solar vehicle, or in short SSV, has been finished successfully. Not only the calculation of every small detail of the SSV was an extremely hard task but also a real experience to extend our knowledge as an engineer. It demanded knowledge of the theory, practice and a lot of persistence.

We don't want to take all the credit because our SSV wouldn't have come to this point without the help of the four coaches. Therefore we want to give a special thanks to Pauwel Goethals, Tan Ye, Yunhao Hu and Pieter Spaepen. These coaches gave a weekly seminar with the information on how to build a SSV. But we want to thank in particular Tan Ye because he was our personal coach who helped us greatly along the way.

Besides the four coaches we also want to thank Marc Lambaerts, FabLab manager, who gave an important and informative session about FabLab. FabLab is the Fabrication Lab where we will build a lot of parts for the SSV.

The project was not an easy project, it was a lot of blood sweat and tears but it was an enormous experience to complete as a student.

We hope you enjoy our report.

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# Resume

In this rapport the impact test is discussed, we want to see how the SSV will react during a collision. Parameters are compared with measurements found in case I.

There is also a Sankey diagram created, where it is possible to see the losses. It is very interesting to see the different losses and see where improvements are possible.

A 2D drawing is added to the report. The drawing gives a view on how our SSV-frame developed, and which dimensions it has. The maximum forces in the frame and in weak places are calculated, to get an idea how great a force can be before the car brakes.

At the end there is an exercise we had to solve about the collision of three masses in total. This can be compared to with the car colliding with the ball.

# Introduction

The small solar vehicle, SSV, is a small car entirely driven by solar energy which has to resist multiple impacts with a steel ball. This car was built in account of the EE4 project and has multiple goals. Like mentioned before it has to resist multiple impacts but that's not the only or main goal. The SSV has to be a pièce de resistance, a real masterpiece on different levels. These levels are: innovation, speed, strength and looks.

The EE4 project is a project with the motto 'Make stuff work'. As future engineers this is an important part of our set of skills which makes the project of greater value for the students. Not only the part of making stuff work is important but also having the background of different fields of science is crucial like: aerodynamics, dynamics, strength of material, technology of materials, algebra, and energy. These fields will stand out throughout the report.

The needs of all these fields are explained quit easily by explaining the project. The SSV will compete in a race in which it has to accelerate as fast as possible. After having accelerated for 10 meters the car has to face a metal ball of 735 grams which it will have to push as high as possible on a ramp. The car cannot break because it has to compete in multiple races. All the different fields are needed to create this SSV.

The race shows only one of the two important criteria of becoming the best SSV. Like mentioned before, the SSV has to be a pièce de resistance. Therefore it has to look good. This is the second criteria it will be quoted on. The entire design but also the appearance is a crucial part.

This report is written by the members of the team Light Weight who will try to fascinate you with their masterpiece.

This cases deals with the actual build of the SSV as well as the tests that needed to be performed to see if car will perform good on the day of the race.

# 1. Impact test

The car is tested with a Piëzo-electrometer to test its reaction upon impact.

## The test

To get an idea about the forces that will impact on the car during the collision, there was a small impact test. This test consists of a weight of 750 grams, which is about the same as the ball that will hit the car. The weight is attached with a rope to a wooden construction. The mass was pulled up to a certain height and released in order to get a collision with the SSV. The same test could be done when we let the car ride against the mass, but we only did the first test.

Figure 37 Wooden construction

To get some information about this test, there was a Piëzo-electrometer attached to the mass. The Piëzo-electrometer is made of a complicated material (it's actually a semi-conductor) which generates a certain voltage when it's compressed. The meter can only measure dynamic forces and not static forces because when there is a static force, there will be no difference in the voltages so it's impossible to measure the force. The Piëzo meter will generate a certain voltage which is measured every 1e-5 of a second.

### Specifications Piëzo-electrometer

*Sensitivity: 56, mv/KN*

This is the voltage output per kilo Newton (unit of force). The amplitude of the AC signal will correspond to the amplitude of the vibration measured. The proportion is the same.

*Electric/spectral noise:*
This parameter depends on the force supplied to the Piëzo-meter. Low forces will have larger error due to the force/noise ratio.

*Maximum static force: 133.44 kN*
This is not the maximum dynamic force. It's the static force that can be applied. Important to note is that the Piëzo-meter can't measure a static force. It generates an electrostatic field which will empty after a certain amount of time (discharge time > 2000sec). That means that the static force will decrease for the Piëzo-meter after 2000sec while it is still there.

Before the signal is sent to the DAQ (data acquisition), the amplifier amplifies the signal by a factor of 100. After the amplification of the signal, the amplitude of the noise will be 10 times higher. It gives a better margin of error and is more precise. Now we can see the differences on the graph better. The DAQ will process the information to a program, where the voltages are registered and plotted.

**Figure 38 On the left amplifier, on the right the DAQ**

Thousands of signals were registered and plotted into a graph. The test was executed three times and each graph has got the same shape and the three same peaks. The three peaks mean that the mass will have 3 times contact during one collision. We can't see these contacts. The expectation was that the first peak would be the highest, during the first contact because the most energy is transferred. But on the graph there is a smaller peak first. There is a hypothesis for that: the accelerometer is attached to the mass and during the collision the mass will have some delay. The Piëzo hits the ball first and that is the first peak, after that, the mass joins the Piëzo-meter that is the second peak. So the first peak is the collision of the SSV with only the meter and the second peak is the collision of the SSV with the Piëzo-meter plus the mass (which had some delays during the first peak).

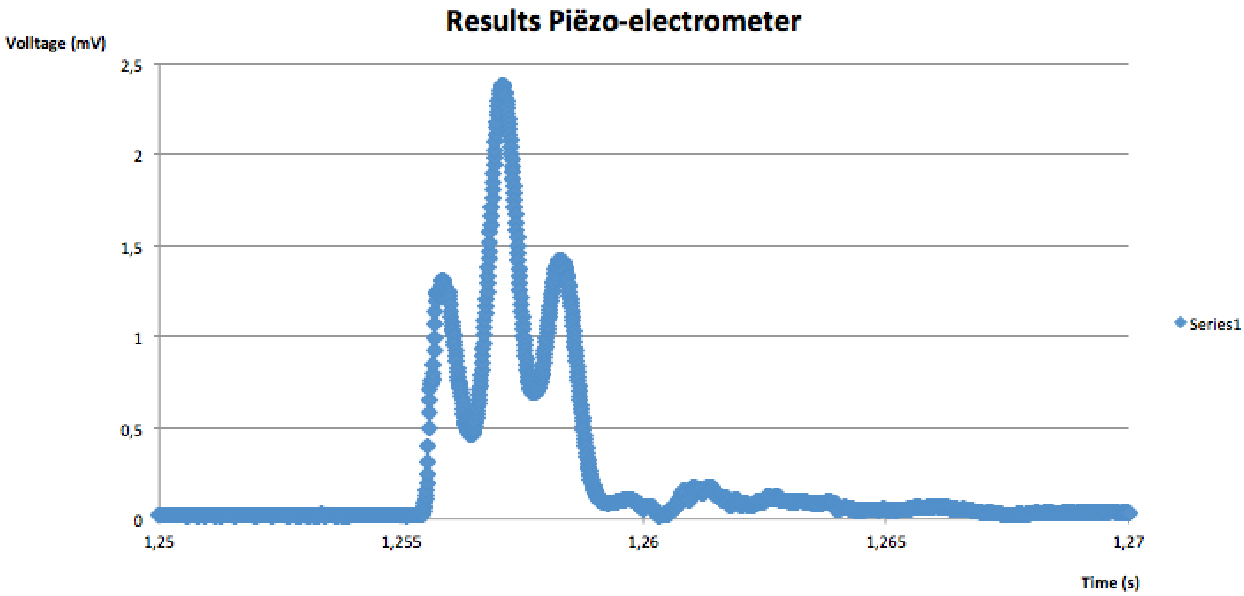



Figure 39 Results Piëzo-electrometer

Besides the measurements from the Piëzo-electrometer, the length of rope (L) and the distance (X) from the mass to the SVV were measured.

L = 1.2m
X1 = 0.25m
X2 = 0.54m
X3 = 0.97m

## 1.2 Coefficient of restitution

The coefficient of restitution can be determined out of the graph. The highest peak is at 2.3V and at this moment the largest energy is transferred. After the first peak there is an action-reaction moment, some of the energy will be lost. The last peak measures 1.4 V, this is the moment when the car leaves the mass. The ratio of these measurements will approach the Coefficient of restitution. We take measurements of the last because this is the most significant. Because the restitution coefficient is dependent on the forces you apply on the object. A low force isn't significant for the calculations because the force/noise will be lower, the higher the force the more accurate the results will be (but it's important the Piëzo or SSV doesn't brake). This is because the noise is a constant and the force/noise ratio will be bigger with a bigger force, it will be more accurate.

$$Cr = \frac{1.4}{2.3} = 0.60$$

If we compare this with the result we did in case SSV 1 where the Cr was 0.85, we can conclude that this is an ok result but there are still some error. For example: the Piëzo-meter didn't hit the ball in the exact centre of the ball which will cause a less accurate result. The golf ball is in fact a good object to hit the steel ball, it won't absorb all of the energy and also damps the collision a little.

## 1.3 Speed of the car

Based on the information it is possible to calculate the speed of the car after it has been hit by the mass. With the following formula it's possible to measure the speed of the car.

$$F \cdot \Delta t = m \cdot \Delta v$$

F = average force on the car
Delta t = time interval of the collision
m = mass of SSV = 1.5 kg
Delta v = speed of the car

The average force of the car can be calculated with the results of the Piëzo-electrometer. The average voltage measured divided by the sensitivity constant and then multiplied with the amplification factor gives the force (the entire calculation is written down in 1.4. for other examples). The time interval can be read of the graph from the results. The mass of the car is a known factor so it's possible to determine the speed.

The speed of the SSV will be 1.014 m/s.

## 1.4 Conversion of the data

The datasheet provides the sensitivity of the PCB200C20 (Piëzo model). The data can then be converted into Newton; this is useful to interpret the data properly. The general formula is:

$$\frac{y}{a} = x \cdot s$$

$$y = x \cdot 100 \cdot 56.2 \cdot \frac{mV}{kN}$$

With:

y = the measured voltage (V)
x = the measured force (N)
a = the amplifier factor (100 [dimensionless])
s = sensitivity is the voltage output per newton (56.2 [mV/kN])

The formula must be converted to get the force:

$$x = \frac{y}{56.2 \times 10^{-4} \frac{V}{N}}$$

*Peak values*

| Height(m) | Voltage(V) | Force(N) |
|---|---|---|
| 0.026 | 0,229792 | 40,88 |
| 0.12 | 1,17616 | 209,28 |
| 0.49 | 2,375262 | 422,64 |

*Departure values*

| Voltage(V) | Force(N) |
|---|---|
| 0,174354 | 31,02 |
| 0,832115 | 148,06 |
| 1,40089 | 249,26 |

The peak values are the values at the moment the Piëzo-meter plus mass hits the car. This will be used in the strength analysis. The departure value is the force that the ball is going to absorb. It can be used to calculate the restitution coefficient.

### Conclusion

With this test it is possible to recalculate the parameters from our previous report and compare them. We can conclude that there is a little difference between them, which means that this a representative test. The test gave a better view of how the car will react on the collision, and the parameters are more specific for the car. The SSV survived the collision, it is strong enough to resist the impact (see calculation forces). The golf ball is a good object to hit with, because it has also the capacity to damp (this has as result the balls will take the hit and not the frame which is good). During the test there was only 1 golf ball attached to our SSV, and this surface is too small to hit. It is possible that we miss the steel ball, because of that some improvements were done to our SSV. A second golf ball and a steel plate were installed, which connects the two golf balls. Now is the surface bigger and now the SSV will surely hit the steel ball. The weight of the car was also a little too high that is why some mass was removed.

## Sankey-diagram

The Sankey-diagram is used to show the energy flow in a certain process. To use that for an SSV, the losses have to be determined. This text was structured according to the energy flow.

### The Sankey diagram at maximum velocity on an infinitely long track

#### The Solar Panel (93.68%)

To find the efficiency, we need the input of the sun. In Belgium the radiation is considered to be 800W/m$^2$ (we used the same in the simulation). The surface of the solar panel was taken from the data sheet.

$$P_{sun} = A_{solar\ panel} \times E_{sun}$$

$$P_{sun} = 16 \times (0.039m \times 0.078m) \times 800 \frac{W}{m^2}$$

$$P_{sun} = 38.9W(100\%)$$

To find the actual power delivered by the solar cells there is a certain pattern to follow. The power delivered is dependent on the load.

The car has a speed of 4.5m/s that means that the gear attached to the driven wheel turns at a certain speed.

$$Speed\ driven\ gear: \omega_b = \frac{v}{2\pi r} = \frac{270\ m/min}{2\pi \times 0.04\ m} = 1074.29\ rpm$$

$$Speed\ driver\ gear: \ \omega_a = \omega_b \times gear\ ratio = 1074.29 \times 7.5 = 8057.22\ rpm$$

When the speed of the motor is known, the back EMF can be calculated:

$$E = K_e \times \omega_a = \frac{1}{1120\ rpm/V} \times 8057.22\ rpm = 7.19\ V$$

The back EMF can be used to find the current delivered by the Solar Panel. The current that the solar panel delivers is the following

$$I(t) = I_{sc} - I_s\left(e^{\frac{E(t)+I(t)R}{mNUr}} - 1\right)$$

$$0 = I_{sc} - I_s\left(e^{\frac{E(t)+I(t)R}{mNUr}} - 1\right) - I(t)$$

This can be solved numerically with the bisection method, which has been handled in case SSV 1 (only the results are shown). The best choice is here 0.3A.

x = 0.4 y(0.4) = -0,69
x = 0.35 y(0.25) = -0,1337
x = 0.3 y(0.3) = -0.098
x = 0.25 y(0.25) = -0,3424

The Power delivered by the solar panel can now be calculated.

$$P_{solar\ panel} = U \times I = (E + R_a \times I) \times I = (7.19V + 3.36\Omega \times 0.3\text{A}) \times 0.3\text{A}$$

$$P_{solar\ panel} = 2.46\ \text{W}$$

$$P_{loss\ solar\ panel} = P_{sun} - P_{solar\ panel} = 38.9W - 2.46W = 36.44W$$

This means that only a small portion of the sun will be used by the solar panel. This is due to reflection and thermal losses.

### The DC-motor (0.77%)

The DC-motor has a certain efficiency that is not constant. The efficiency is depended on the load. There is a lack of information on the datasheet, thereby the efficiency of the DC-motor cant' be found. A good approach for the loss of the DC-motor is the inner resistance (it covers most of the loss). The inner resistance is in the datasheet and the current delivered by the solar panel has already been calculated.

$$P_{loss\ DC-motor} = R \times I^2 = 3.36\Omega \times (0.3A)^2 = 0.3W$$

### Air friction (2.99%)

The parameters used for this calculation can be found in SSV case 1. The maximum velocity was found with the Mathlab simulation.

$$F_w = ½ \cdot C_w \cdot A \cdot \rho \cdot v^2$$

$$F_w = 0.5 \cdot 0.5 \cdot 0.03m^2 \cdot 1.293 \frac{kg}{m^3} \cdot (4 \frac{m}{s})^2 = 0.258N$$

$$P_{loss\ air\ friction} = F_w \cdot v = 0.258 \cdot 4.51 \frac{m}{s} = 1.16W$$

### Rolling resistance (2.04%)

$$Fr = Crr \times N = 0.012 \times 1.5\ kg \times 9.81 \frac{N}{kg} = 0.176N$$

$$P_{loss\ rolling\ resistance} = Fr \times v = 0.176 \times 4.51 \frac{m}{s} = 0.795W$$

### Gears and remaining losses (2.7%)

The remaining losses will be attributed to the gears, shaft and bearings friction.

$$P_{loss\ gear} = P_{motor} - P_{loss\ rolling\ resistance} - P_{loss\ air\ friction}$$

$$P_{loss\ gear} = 2.46W - 0.3W - 0.258W - 0.795W = 1.047W$$

In this status the velocity has reached its maximum and is constant. The SSV is in equilibrium because all the delivered power is compensated by the losses. There is no power left to accelerate. In this case we can assume that the resting power can be allocated to the gears, bearing and shaft. This will be useful for the calculation at half speed.

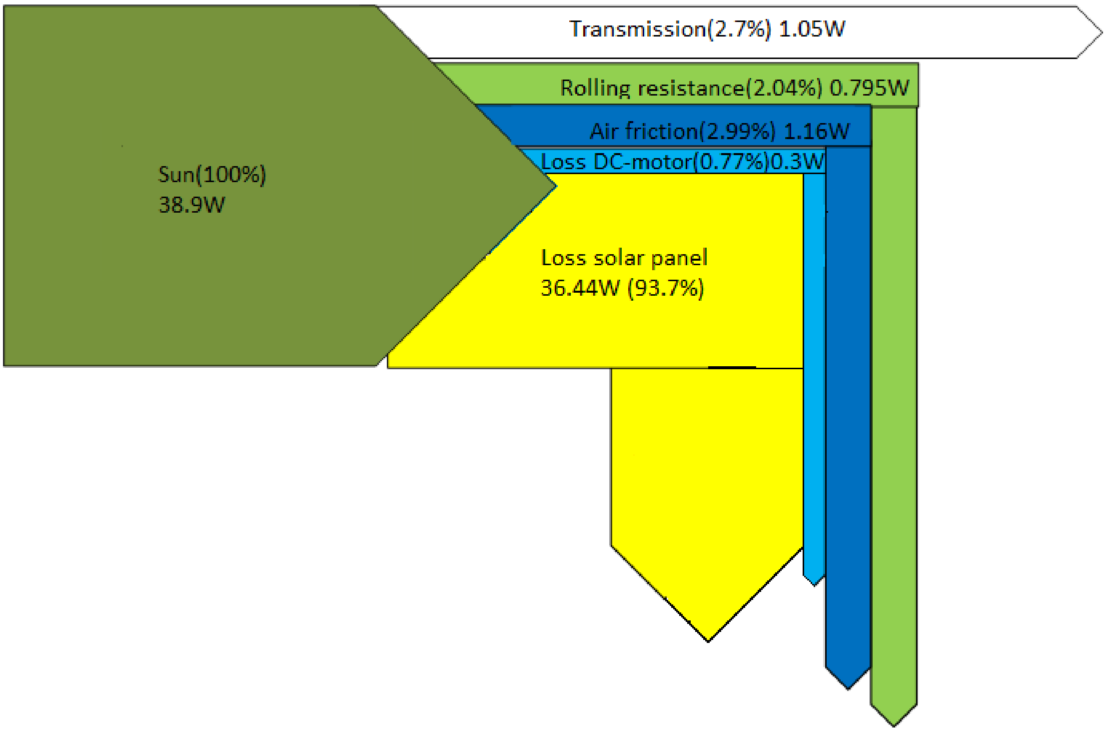



Figure 40 Sakey diagram

## The Sankey diagram at half of the maximum velocity on an infinitely long track

The load has changed, so has the power delivered by the solar cell. The Sankey Diagram has to be calculated again. Only the Transmission losses will be held constant.

### The Solar Panel (82.37%)

The power delivered by the sun is still the same.

$$P_{sun} = 38.9W(100\%)$$

The car has a speed of 2.25m/s that means that the gear attached to the driven wheel turns at certain speed:

$$Speed\ driven\ gear: \omega_b = \frac{v}{2\pi r} = \frac{135\ m/min}{2\pi \times 0.04\ m} = 537.15\ rpm$$

$$Speed\ driver\ gear: \ \omega_a = \omega_b \times gear\ ratio = 537.15 \times 7.5 = \ 4028.61\ rpm$$

When the speed of the motor is known, the back EMF can be calculated:

$$E = K_e \times \omega_a = \frac{1}{1120\ rpm/V} \times 4028.61\ rpm = 3.60\ V$$

The back EMF can be used to find the current delivered by the Solar Panel. The current that the solar panel delivers is the following

$$I(t) = I_{sc} - I_s\left(e^{\frac{E(t)+I(t)R}{mNUr}} - 1\right)$$

$$0 = I_{sc} - I_s\left(e^{\frac{E(t)+I(t)R}{mNUr}} - 1\right) - I(t)$$

This can be solved numerically with the bisection method, which has been handled in case SSV 1 (we will only show the results). The best choice is here 0.99A.

x = 1.05 y(1.05) = -0,025
x = 0.99 y(0.99) = -0.001
x = 0.95 y(0.95) = 0.051

The Power delivered by the solar panel

$$P_{solar\ panel} = U \times I = (E + R_a \times I) \times I = (3.60V + 3.36\Omega \times 0.99\text{A}) \times 0.99\text{A} = 6.86\ \text{W}$$

$$P_{loss\ solar\ panel} = P_{sun} - P_{solar\ panel} = 38.9W - 6.86W = 32.042W$$

This means that only a small portion of the sun will be used by the solar panel. This is due to reflection and thermal losses.

### The DC-motor (8.46%)

The loss of the DC-motor has considerably risen compared at full-speed. This is due to the current the solar panel is delivering at half speed.

$$P_{loss\ DC-motor} = R \times I^2 = 3.36\Omega \times (0.99A)^2 = 3.29W$$

### Air friction (1.49%)

$$P_{loss\ air\ friction} = F_w \cdot v = 0.258 \cdot 2.25\frac{m}{s} = 0.580W$$

### Rolling resistance (1.01%)

$$P_{loss\ rolling\ resistance} = Fr \cdot v = 0.176 \cdot 2.25\frac{m}{s} = 0.396W$$

All the losses have to be added to determine the total loss of the SSV.

$$P_{loss} = P_{loss\ solar\ panel} + P_{loss\ motor} + P_{Transmission} + P_{loss\ air\ friction} + P_{loss\ rolling\ resistance}$$

$$P_{loss} = 32.04W + 3.29W + 1.05W + 0.580W + 0.396W = 37.92W$$

The following is to find the remaining power for the acceleration of the car.

$$P_{surplus} = P_{sun} - P_{loss}$$

$$P_{surplus} = 38.9W - 37.35 = 1.54W(4\%)$$

At half speed the SSV has 1.54W left. This means that the SSV will use this to accelerate to its maximum speed.

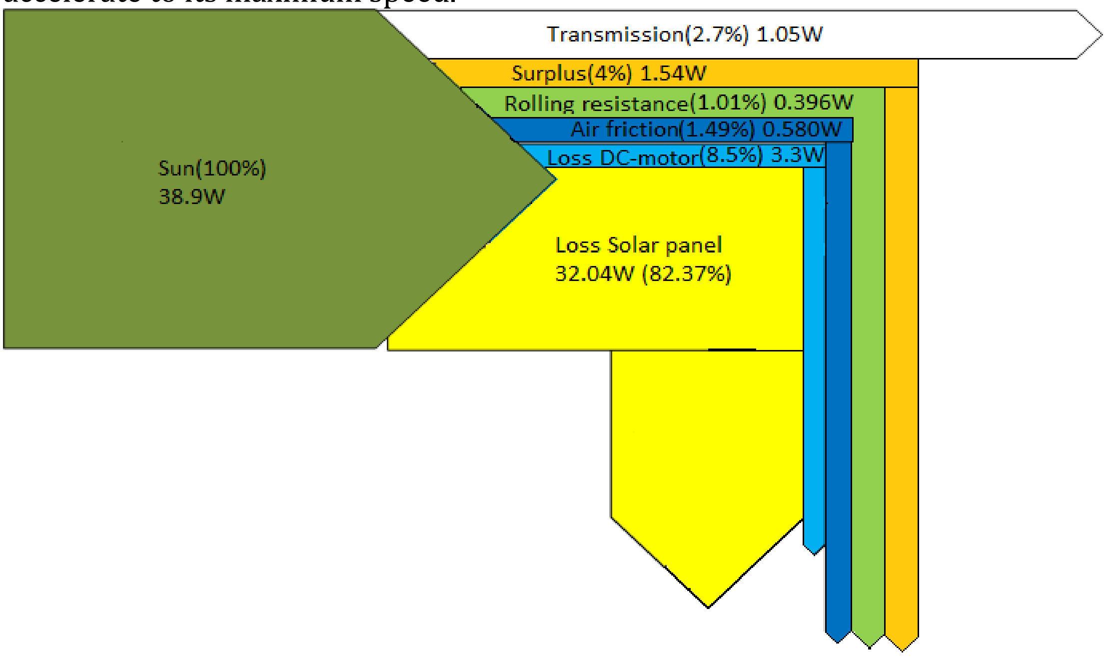



Figure 41 Sankey diagram II

## 2D technical drawing

In figure6 the technical drawing in 2 dimensions of the frame of the car can be found. Based on the information of the seminars of dimensioning, the measurements are correct attached to the drawing.

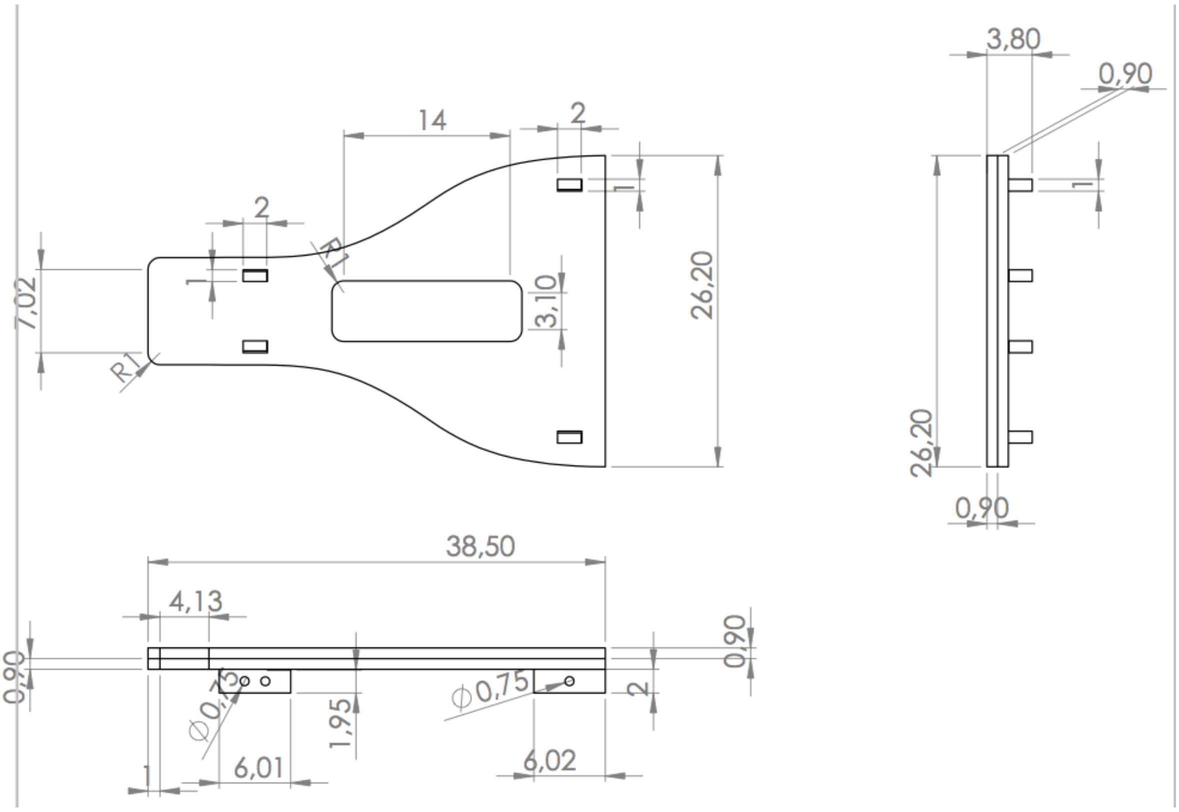



Figure 42 2D technical drawing

# Strength calculations

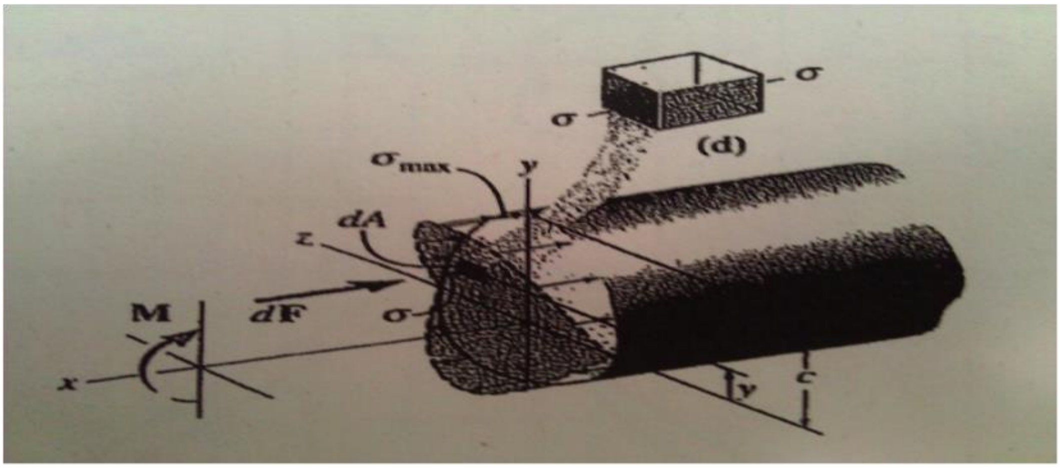



Figure 43 Forces and momentum

Because the solar panel has a lot of different levels, the possibly crucial forces will be due to momentum. Shearing is not possible, because the steal L shape will bend first before it will break the screws also there are 4 thick screws used.

## Point 1

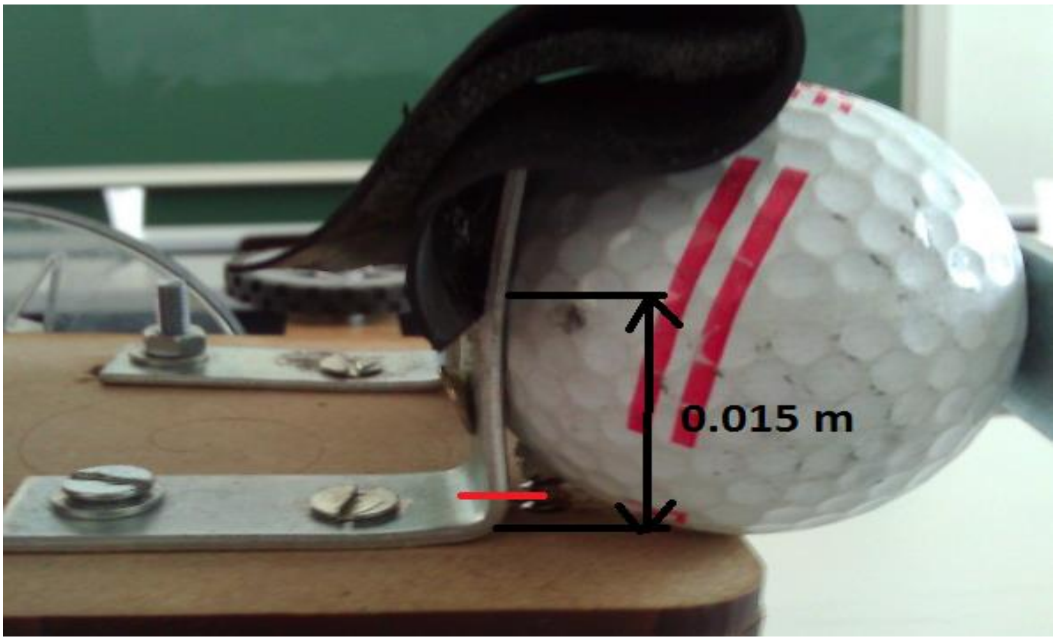
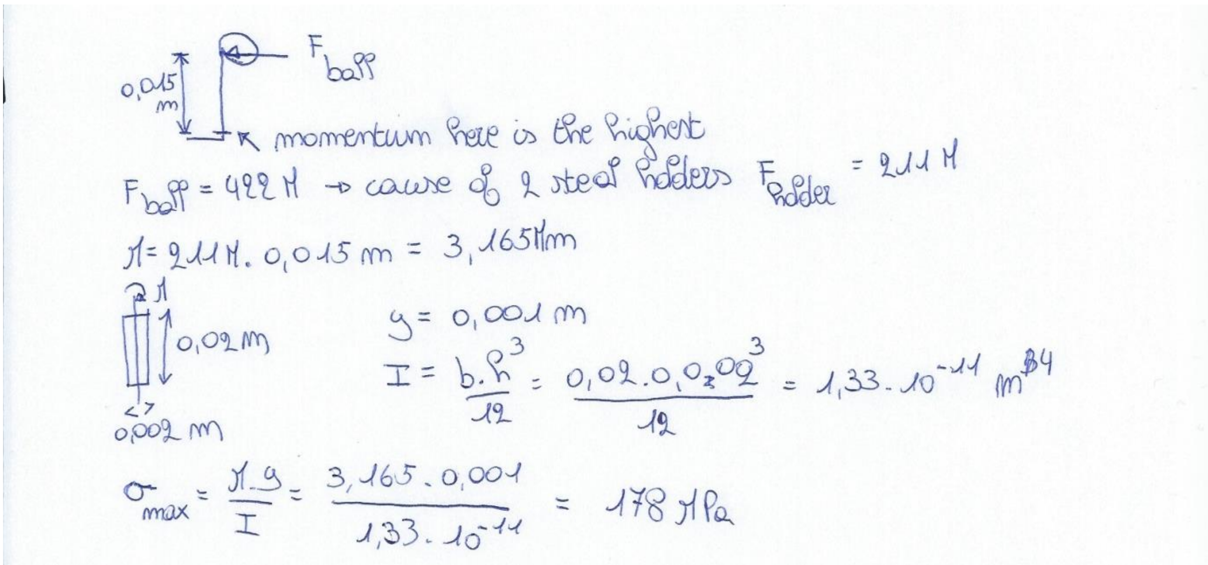



Figure 44 Golf ball with L-frame

The steel L-frame that holds the ball is the first point which might break, the moment is here the highest at the lowest point before the bend:




$F_{ball} = 422\,N$ → cause of 2 steel holders $F_{holder} = 211\,N$

$M = 211\,N \cdot 0{,}015\,m = 3{,}165\,Nm$

$y = 0{,}001\,m$

$I = \frac{b \cdot h^3}{12} = \frac{0{,}02 \cdot 0{,}002^3}{12} = 1{,}33 \cdot 10^{-11}\,m^4$

$\sigma_{max} = \frac{M \cdot y}{I} = \frac{3{,}165 \cdot 0{,}001}{1{,}33 \cdot 10^{-11}} = 178\,MPa$

The value of 178MPa is safe; it will not bend. The maximum bending stress for this type of steel is about 250MPa (construction steel).

## Point 2

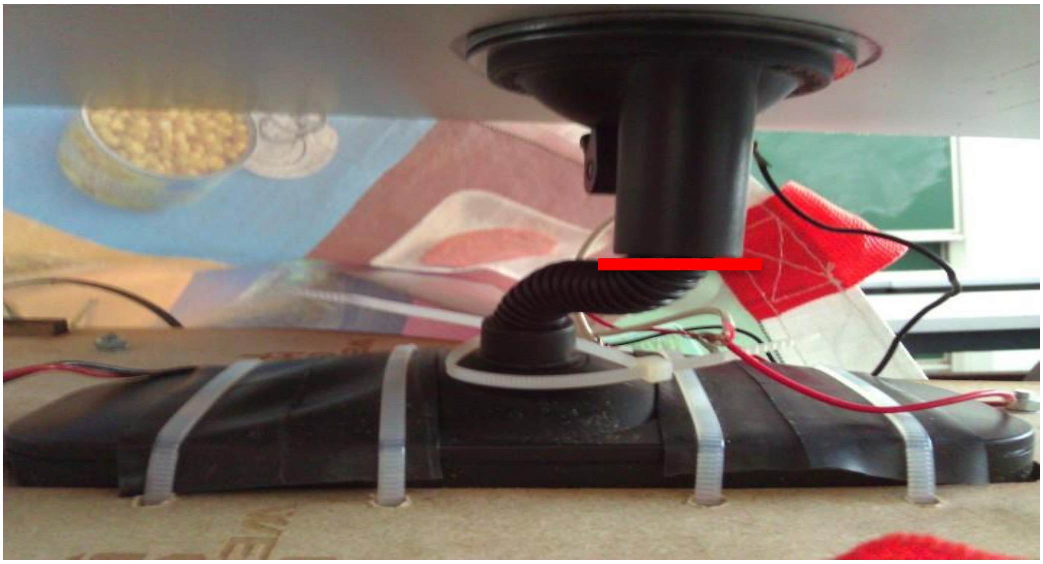
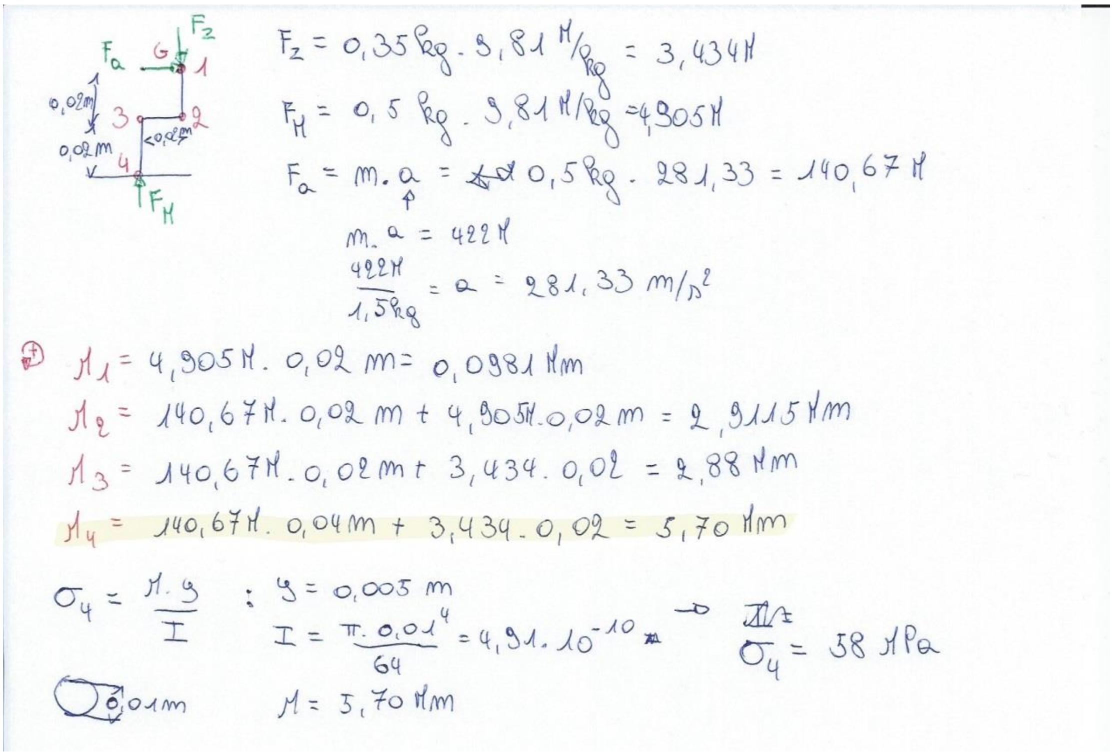


**Figure 45 Holder Solar panel**

Another possible critical point is the solar panel holder; it sticks out above the car which creates a large momentum at the time of collision. The car will decelerate to a standstill but the solar panel will keep moving forward for an instant. At this point the moment forces are the biggest. To prevent the holder from breaking it has a thick 1 cm diameter and is made out of steal (not pure steel because that's not that easy to bend but here will be assumed it's just steel for simplicity). The point of maximum momentum is not clear from the beginning, therefore the momentum for four different places are calculated.


$F_z = 0,35\,kg \cdot 9,81\,N/kg = 3,434\,N$

$F_N = 0,5\,kg \cdot 9,81\,N/kg = 4,905\,N$

$F_a = m \cdot a = 0,5\,kg \cdot 281,33 = 140,67\,N$

$m \cdot a = 422\,N$

$\frac{422\,N}{1,5\,kg} = a = 281,33\,m/s^2$

$M_1 = 4,905\,N \cdot 0,02\,m = 0,0981\,Nm$

$M_2 = 140,67\,N \cdot 0,02\,m + 4,905\,N \cdot 0,02\,m = 2,9115\,Nm$

$M_3 = 140,67\,N \cdot 0,02\,m + 3,434 \cdot 0,02 = 2,88\,Nm$

$M_4 = 140,67\,N \cdot 0,04\,m + 3,434 \cdot 0,02 = 5,70\,Nm$

$\sigma_4 = \frac{M \cdot y}{I}$ ; $y = 0,005\,m$

$I = \frac{\pi \cdot 0,01^4}{64} = 4,91 \cdot 10^{-10}$ → $\sigma_4 = 58\,MPa$

$M = 5,70\,Nm$



After calculations the maximum momentum is found to be at the bottom point of the flexible arm. The bending stress of 58 MPa is also safely lower than the maximum bending force of 250 MPa.

## 5 The collision process

This is a small exercise to fully understand the collision process. There are three masses, mass A,B and C which are moving frictionless on a surface. A and B both have a mass of 2 kilograms and a speed of 6 meters per second. C has a mass of 4 kilograms and stands still. The spring between A en B is long enough for the masses not to hit. The collision of B and C is completely inelastic.

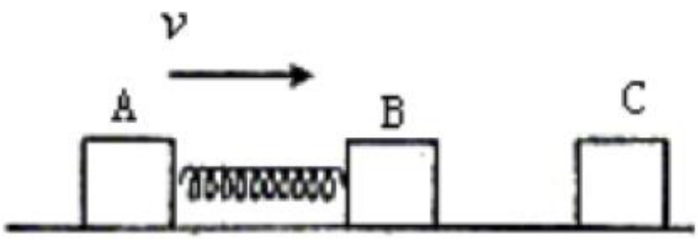



Figure 46 initial situation of the two object before collision

## Question a

*What is the movement speed of object b and c immediately after the impact?*

The collision between B and C is perfectly inelastic. This means that the two objects will move as one object after the collision.
To calculate the final speed of this object (B&C) we will use the following equations:

$$Vc = \frac{Crmb(ub - uc) + mbub + mcuc}{mc + mb} = 2\,\frac{m}{s}$$
$$Vb = \frac{Crmc(uc - ub) + mbub + mcuc}{mc + mb} = 2\,\frac{m}{s}$$

va is the final velocity of the first object after impact
vb is the final velocity of the second object after impact
ua is the initial velocity of the first object before impact
ub is the initial velocity of the second object before impact
mc is the mass of the third object
mb is the mass of the second object
Cr is the coefficient of restitution;

To solve this equation the following parameters are used:
Cr=0 (Because this is an inelastic collision, the coefficient of restitution is zero)
Mb= 2 kg
Mc= 2 kg
Ua= 6 $\frac{m}{s}$
Ub = 0 $\frac{m}{s}$

### Conclusion

This result is convenient because the object b and c will move as one object so the speed will and needs to be the same.

## Question c

*How much is the maximum spring potential energy?*

Like calculated in question a, the speed of object B&C will be 2 m/s immediately after the collision. Because object A has a velocity of 6 m/s, the velocity of A will decrease until the speed of the system is the same. The kinetic energy will go to potential energy in the spring, the spring will push on the system BC so their speed will increase a bit.
This potential energy will have a maximum value when the speed of the whole system is the same. The maximum energy that object A could transport to potential energy in the spring is easy to determine. Immediately after collision, the speed of object A is 4 m/s higher than the speed of object BC. So the difference in (kinetic) energy is:

$$Ekin = \frac{mv^2}{2} = 16j$$

<u>Following parameters are used in the equation:</u>
Ma: (the mass of object a): 2kg
Va: (The speed of object a after collision) = 6m/s
Vb,c: (The speed of the object b and c after collision) = 2m/s

*So the maximum potential energy that the spring could absorb is 16j, this is when speed of the whole system is the same.*

## Question b

First question C is calculated because now it easier to calculate the speed of the whole system when the potential energy of the spring is the highest.
Immediately after the collision the total energy of the system can be calculated by using the equations for the kinetic energy.

**Esystem=Ekin1 + E kin2**

- The kinetic energy of object A is represented by Ekin1.

Ekin1= $\frac{mv^2}{2}$= 36 j
**Parameters:**
Ma = 2 kg
Va= 6m/s

- The kinetic energy of object B&C is represented by Ekin2:

Ekin2= $\frac{mv^2}{2}$= 12 j
**Parameters:**
Mb&c= 6kg
Vb&c= 2 m/s

So now the total energy of the system can be calculated.
Esystem=48 j
After some time the speed of the whole system will be the same, for a short time. This will be when the potential energy in the spring will reach a maximum. The total energy of the system will maintain the same, this is the principle of conservation of energy. But now there are two aspects of energy, there is one part kinetic energy but also some potential energy in the spring.
**Esys= Ekin + Epot**

- Ekin=$\frac{mv^2}{2}$=?

**Parameters:**
Msyst= 8kg
Vsyst= unknown

- Epot=16 j (see question c)

The only unknown parameter in this equation is the velocity of the total system, so the equation can be solved and a velocity of 2.83 m/s was found.

## Question d

Obtained from the momentum conservation

$$ma \cdot v + mb \cdot v = ma \cdot va + (mb + mc) \cdot vb$$

Let A left velocity direction, va>0 then vb > 4m/s.

After the role of A, B, C, and kinetic energy

$$Ek = \frac{1}{2} \cdot ma \cdot va^2 + \frac{1}{2} \cdot (mb + mc) \cdot vb^2 > 48J$$

In fact the system mechanical energy

$$E' = Ep + \frac{1}{2}(ma + mb + mc) \cdot va^2 = 48J$$

According to the law of conservation of energy, Ek > E' is impossible. Therefore, A cannot move to the left.

# Final version of the SSV

In this part the final model of the SSV will be discussed together with all its components and the important decisions that were made.

## Top of the SSV

This is a picture of the SSV at this moment. But in this section only the choice of materials and the construction will be discussed.

In the beginning there were some important choices that had to be made, the material of the frame, wheels,… all these decisions can be read in the report case SSV I. But they will be discussed here shortly. As frame material, mdf was used, this is because it is light, strong, easy to adjust and not very expensive. This has been bought and made at FabLab.

As collision material, a golf ball seemed a good solution. This is because golf ball are hard and have a high restitution coefficient, this will result in a good punch to the ball. In the first case, it was intended to use only one golf ball, this is in fact better for the punch but this makes it harder to hit the steel ball. That's why two golf balls were implemented. Also the two steel L-shaped forms are not chosen randomly. When colliding with the ball they will act as a spring and a spring doesn't lose energy. Also the plate in the front makes it easier to hit the ball but contributes to an effective collision with the ball.

The solar panel is kept in place with a mirror from a car. This mirror has a suction cup at one end en the mirror at the other end connected to each other with a flexible arm. This flexible arm will make sure the solar panel can be directed to sun.

The wheels are made of Plexiglas but this hasn't a specific goal. They are 8 mm thick which is pretty thick but this way they won't break. They also look better than wooden wheels.

The SSV has been provided with some support wheels which will make sure the SSV keeps driving on a straight line. The wheels are from Knexx and are provided with a bearing inside to reduce friction losses.

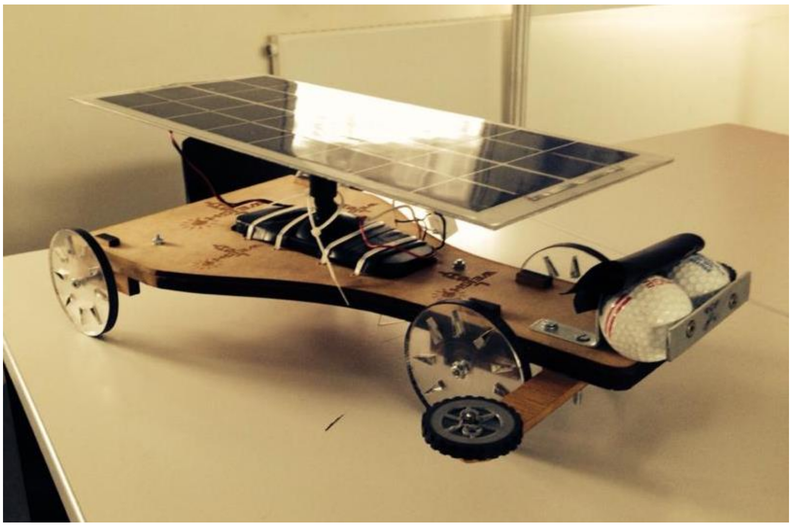


Figure 47Final version of the SSV before paint

After paint the SSV looked like this.

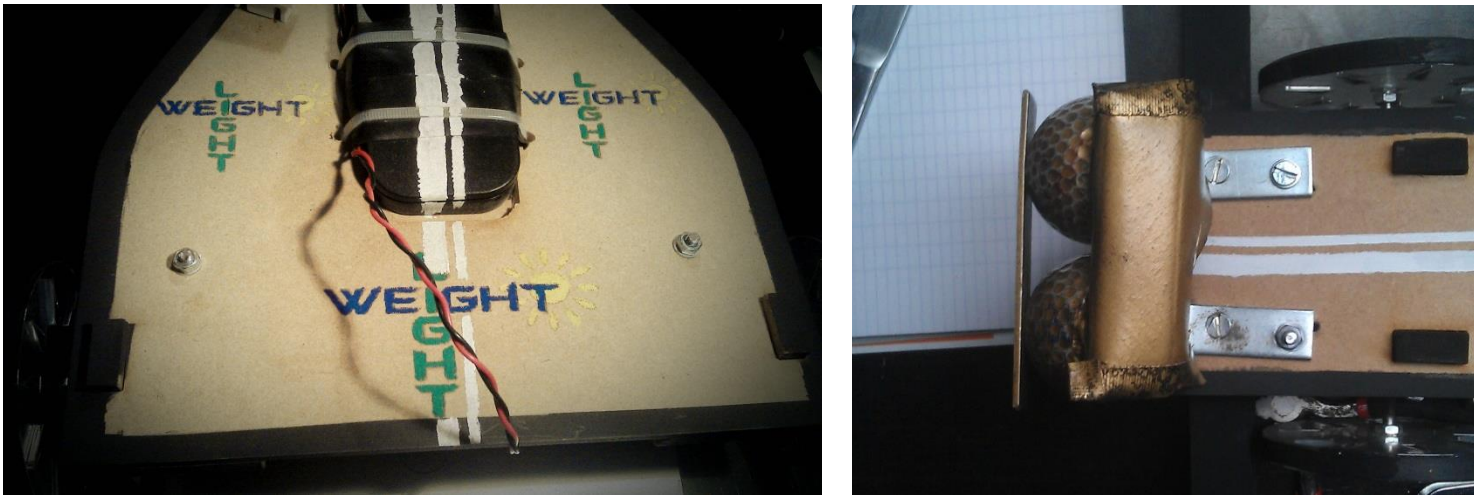


Figure 48 SSV with painted logo and golf balls

The SSV got during paint a race-stripe, the golf balls were painted in gold and the engraved logo was given the right colors.

In the picture below the final version of the SSV can be seen. This picture shows that also the side wheels were given color, they were painted in the white-wall look. On this picture the cables from the solar panel are visible and you can see that they are wound up with each other. This is to reduce the induction currents induced in a conductor.

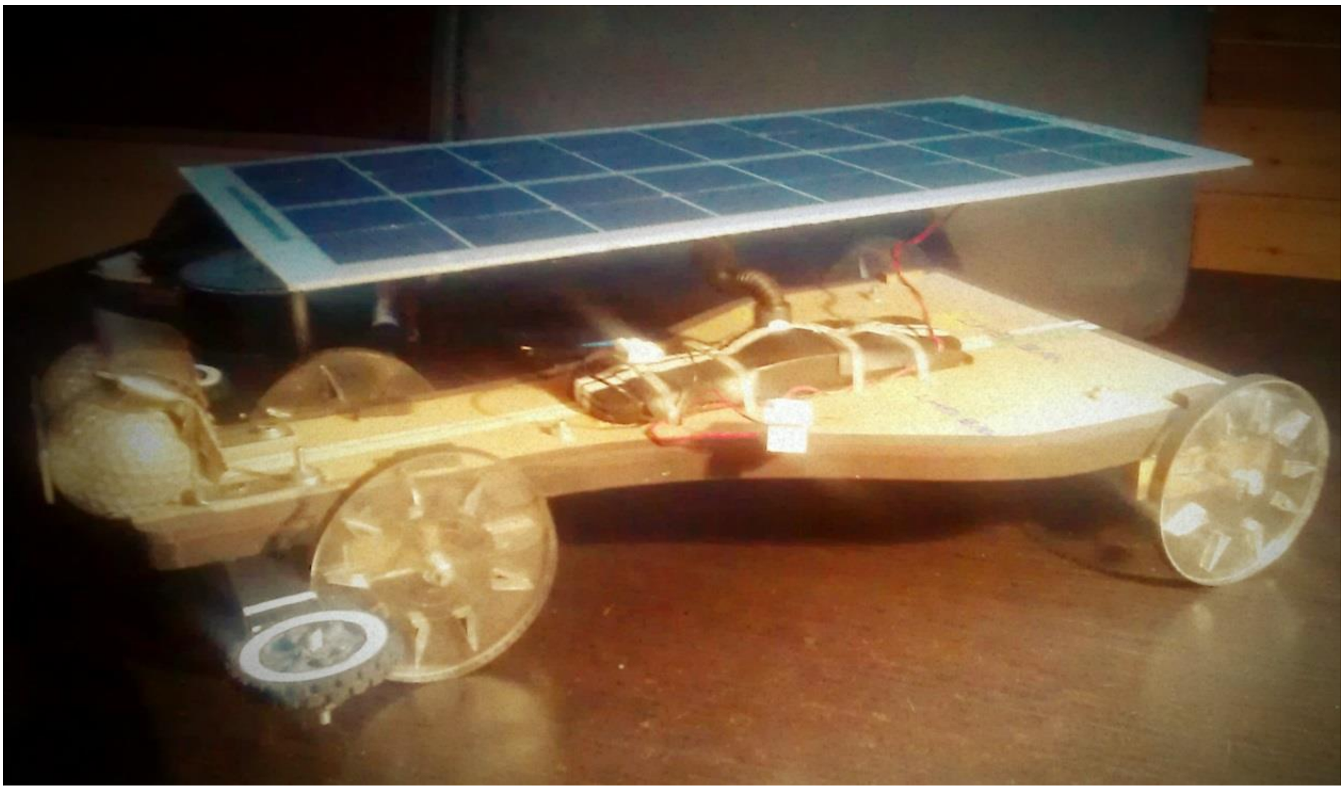


Figure 49 Final version of the SSV after paint

## Bottom of the SSV

On this picture it's easy to see the how the different gears and axles are implemented.

Figure 50 Bottom of the SSV

Every axle (3) visible on the picture is provided with 2 bearing located in the wooden parts. This was actually a tricky part to produce because the bearings can't fall out and they had to stand straight. In the picture below the different parts provided with a bearing can be seen.

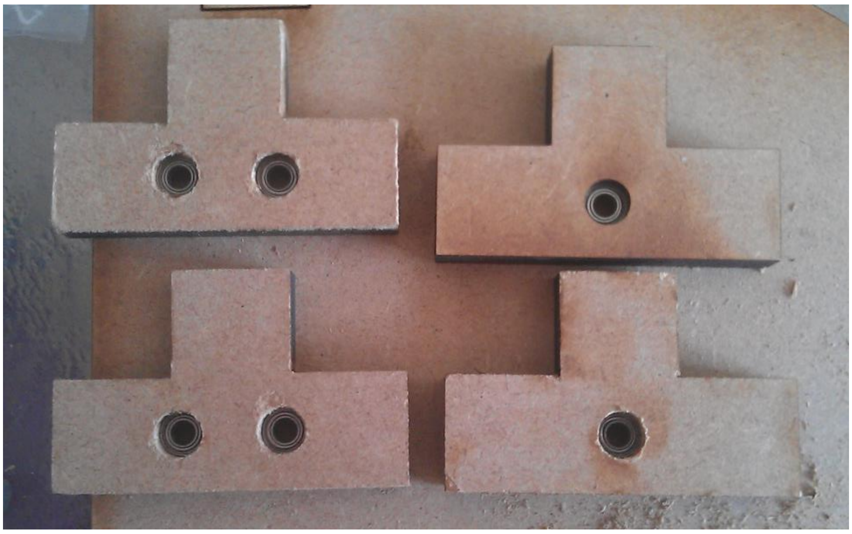


Figure 51 Bearings inserted for the axles

That hardest part was to align the gears perfectly, this is a crucial part for the SSV because this might cause a lot of losses. The motor is kept in place with a metal strip covered with some kind of rubber so the motor can't vibrate or slide out of its place. We chose to use metal gears and ordered them at Conrad, an online store where you can buy parts for RC-cars. This way we were ensured the gear were perfect and wouldn't cause a lot of friction. The only thing that may seem stupid is the use of the gears. We used four gears, but the two small ones are the same and the two big ones are the same. This wasn't chosen for no reason, we know more gears cause more friction but if we wanted to use this type of gear we had to use more than two. Otherwise the motor wouldn't reach the axle of the wheels. We also considered using three gears but this way we couldn't get our ideal gear ratio (the store only had limited sets of gears). The gear themselves are fixed on the axle with small bolts, this way the gear won't slide along the axle.

On the final picture one of the ends of an axle can be seen. To keep the wheel in its place and to prevent them from spinning round the axle they had to be bolted to the axle (if the wheels spin round the axle this will cause more friction than when they spin together with the axle in the bearing). That's why screw-thread was provided to the axles to bolt the wheels with the axles

Figure 52 Axle provided with screw-thread

## Conclusion

This report has dealt with the different factors the SSV has to handle with. These are the different stresses during the impact, the impact itself and the power dissipation. The main result that can be derived from all of these tests is that the SSV will definitely survive the race according to the stress calculations in the weak points. But it will also have a good collision with the ball according to the test with the Piëzo-electrometer. This showed that the golf ball has a good coefficient of restitution which means the kinetic energy from the car will be passed on good. And as last the power dissipated by the engine was calculated and illustrated with a Sankey-diagram. This diagram thought us that only a fraction of the total power generated is efficiently used to move the car, the rest is lost due to friction or other losses.

But as conclusion it's possible to state that the car will survive the test and perform very well during the race.

## Resources

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