SSV Case I

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INTERNATIONALE HOGESCHOOL LEUVEN

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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.

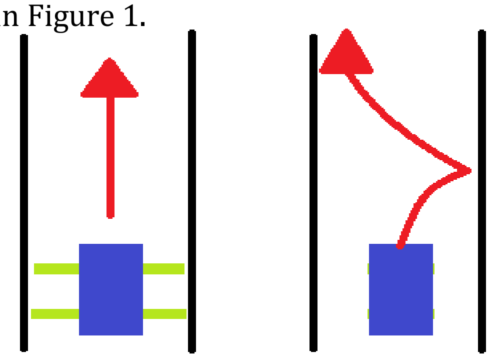


Figure 1: SSV with and without precaution

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'.

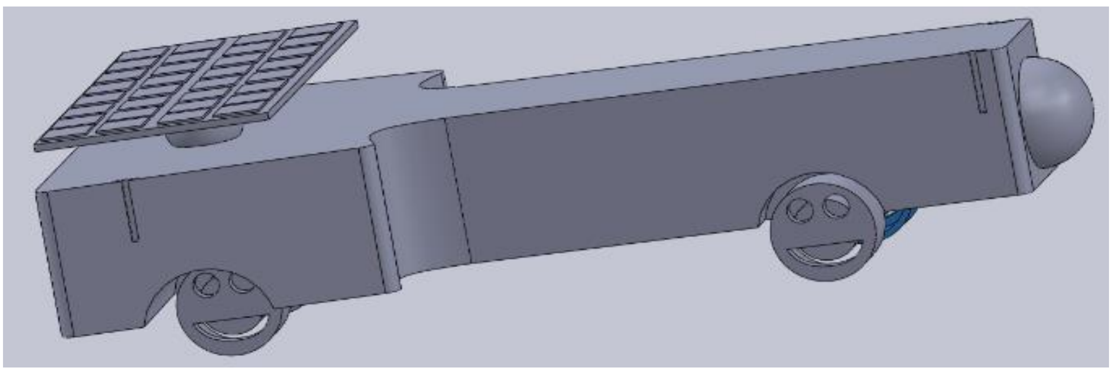


Figure 2: Design in Solid Works

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:

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

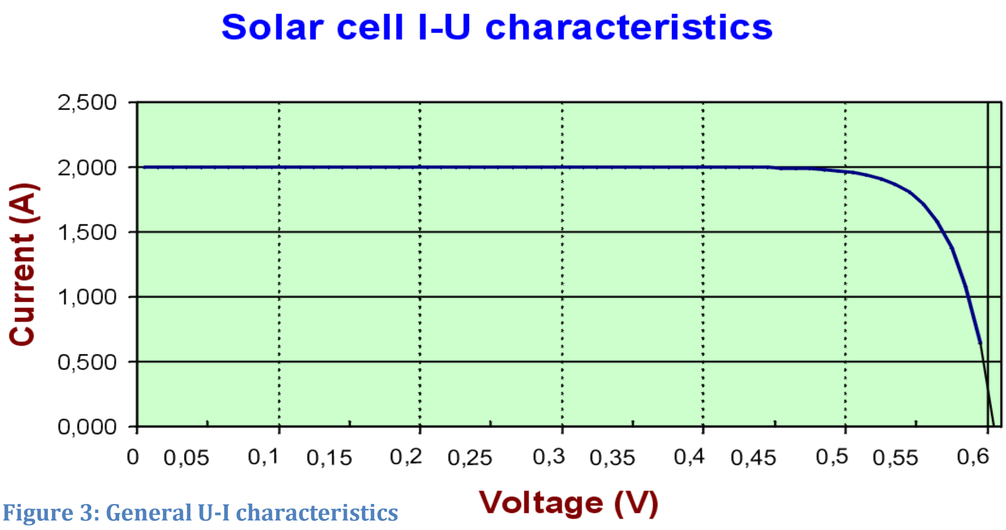


Figure 3: General U-I characteristics

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.

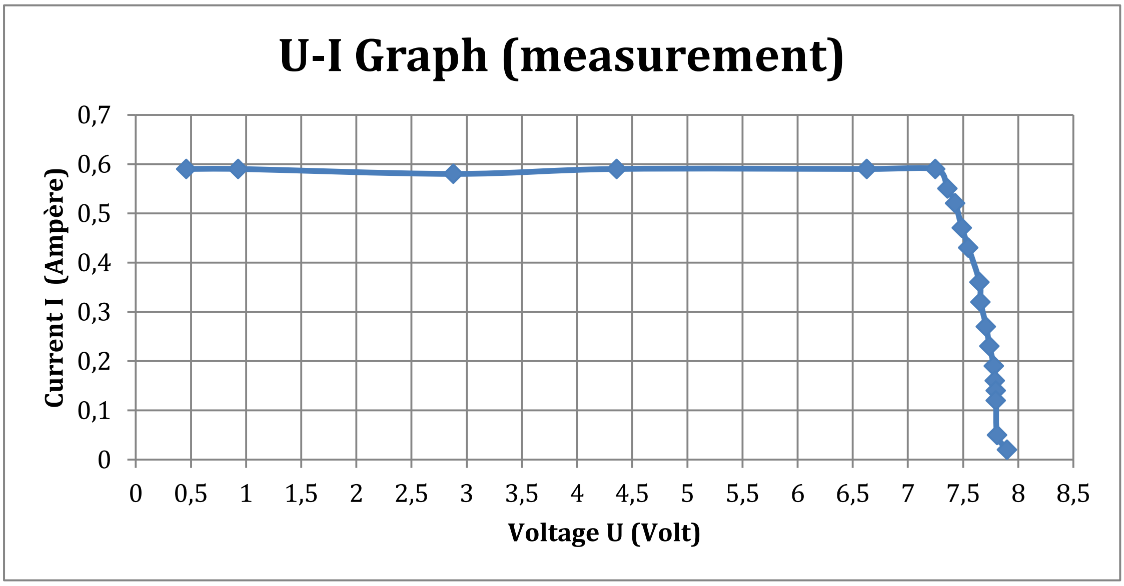


Figure 4: U-I Graph

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.

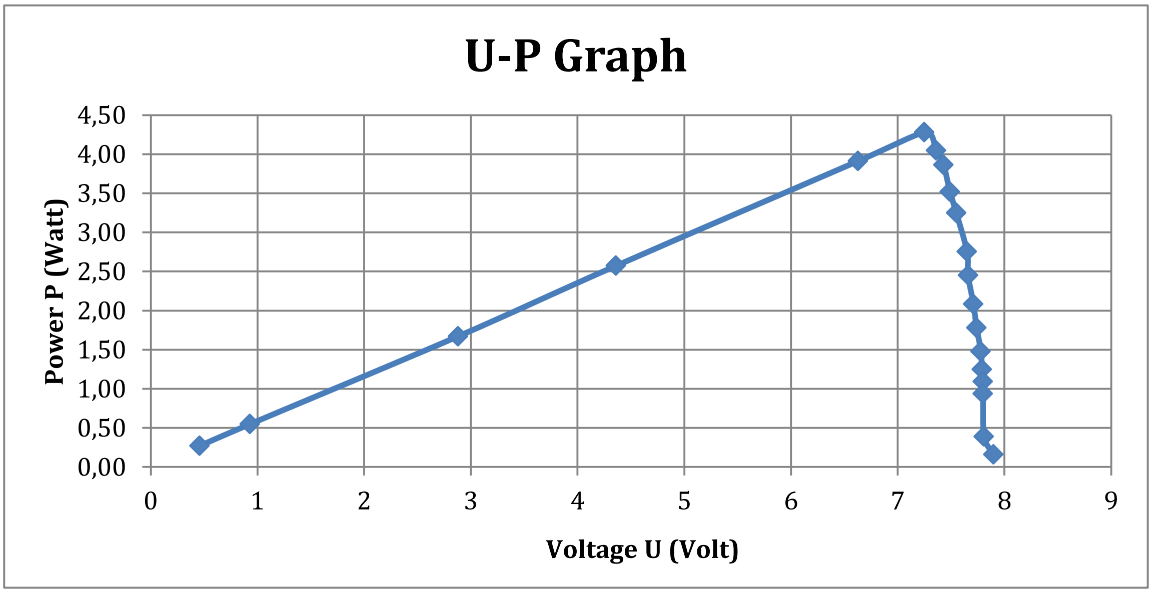


Figure 5: U-P Graph

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.

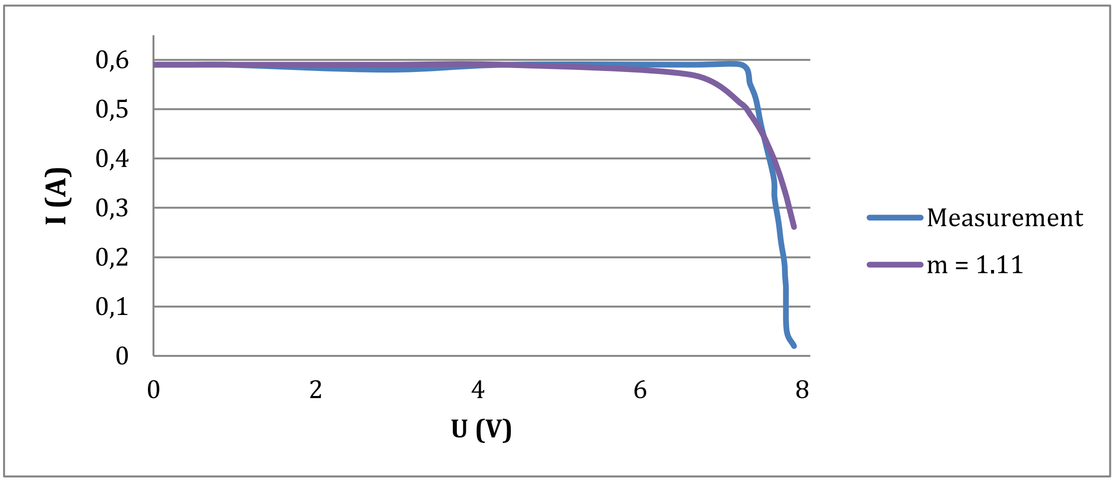


Figure 6: m-value 1.11

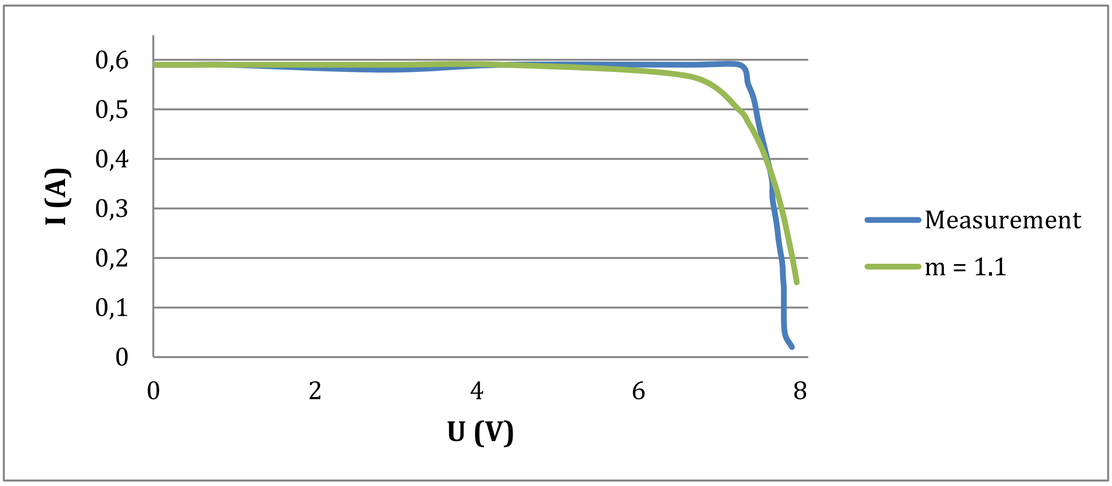


Figure 7: m-value 1.10

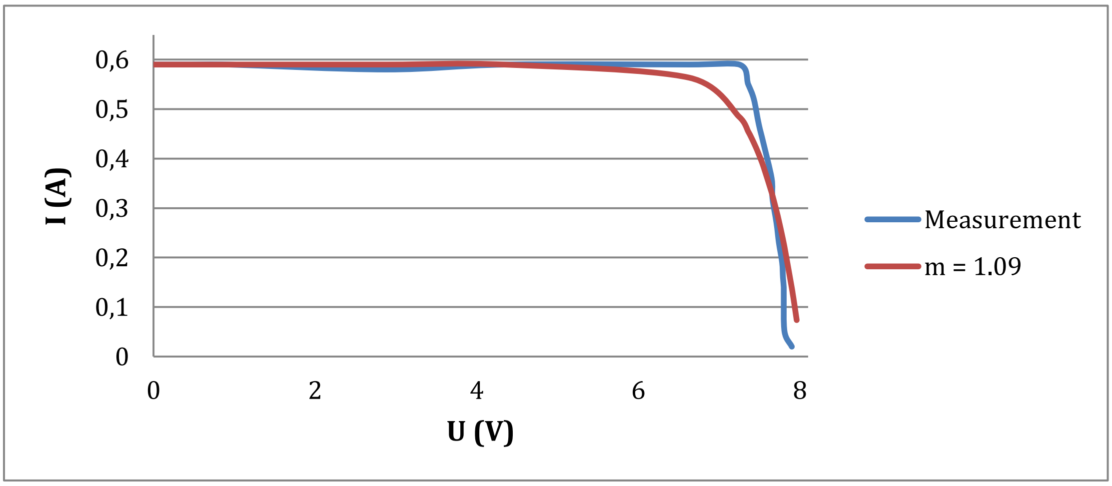


Figure 8: m-value 1.09

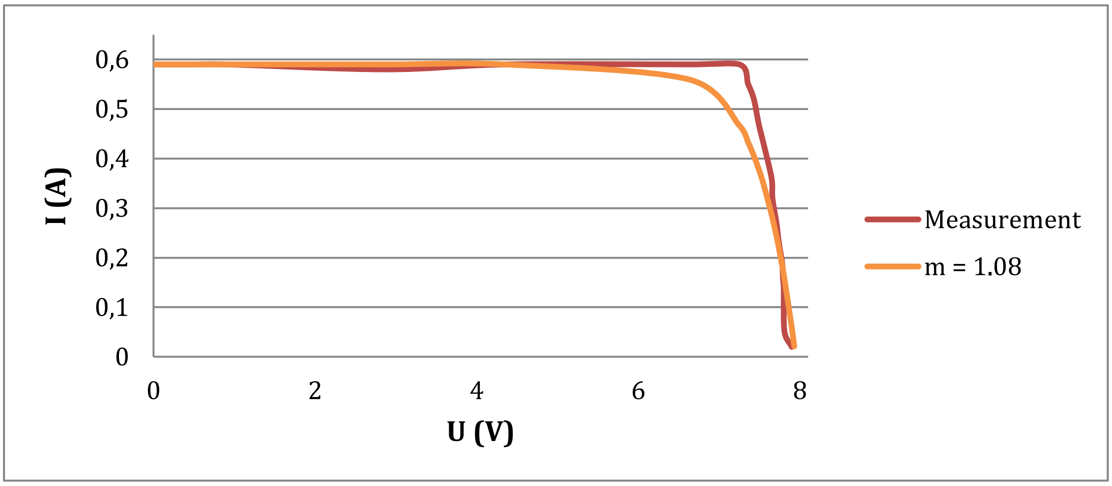


Figure 9: m-value 1.08

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.

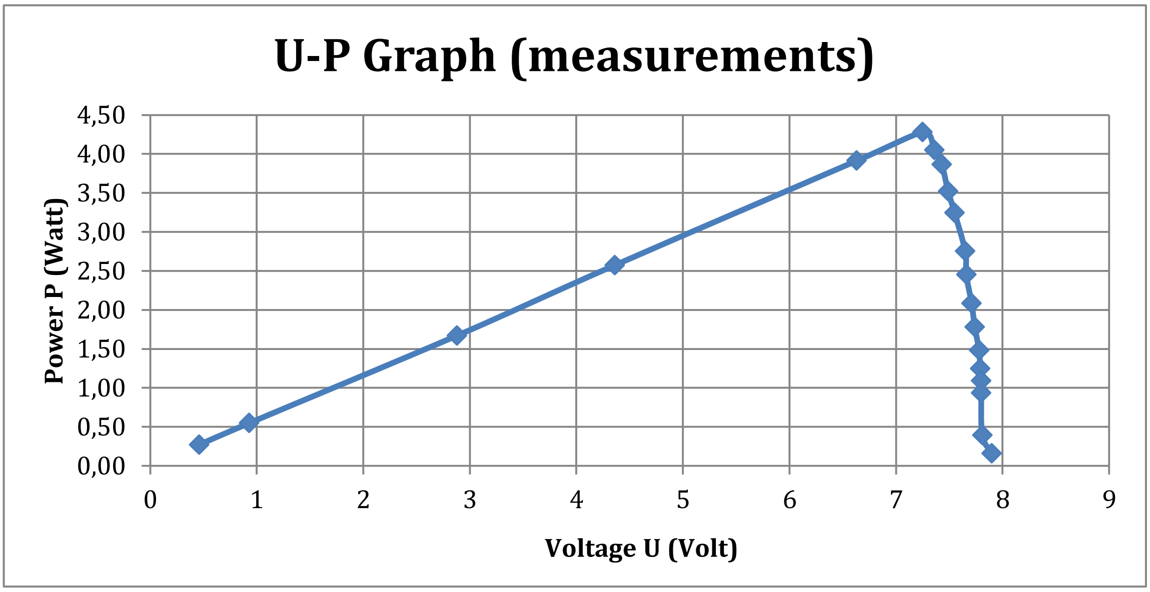


Figure 10: U-P Graph (measurements)

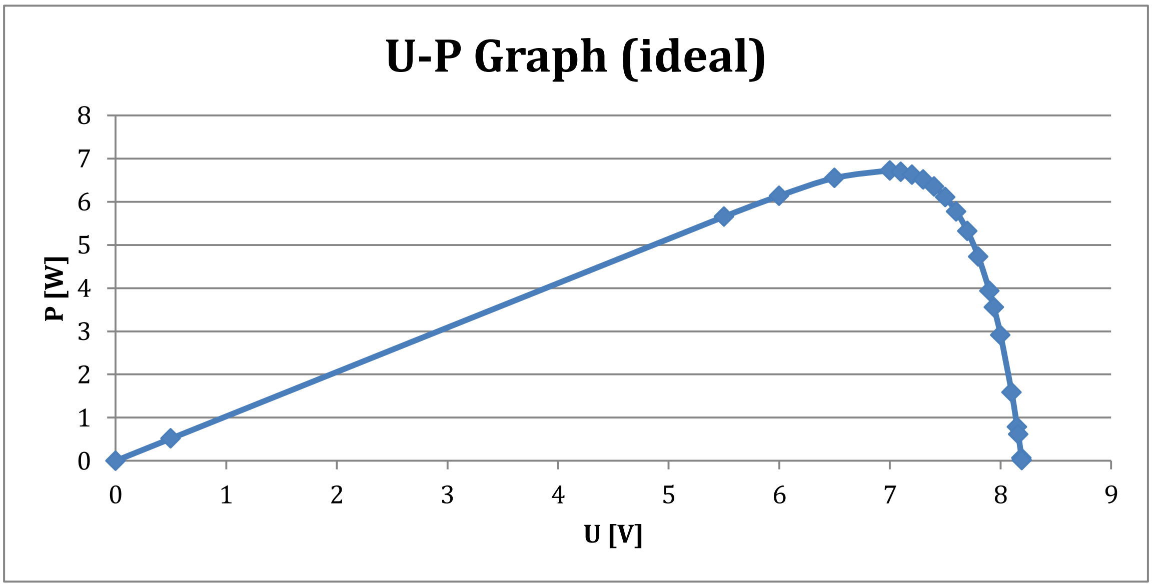


Figure 11: U-P Graph (ideal solar panel)

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
ω = 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.

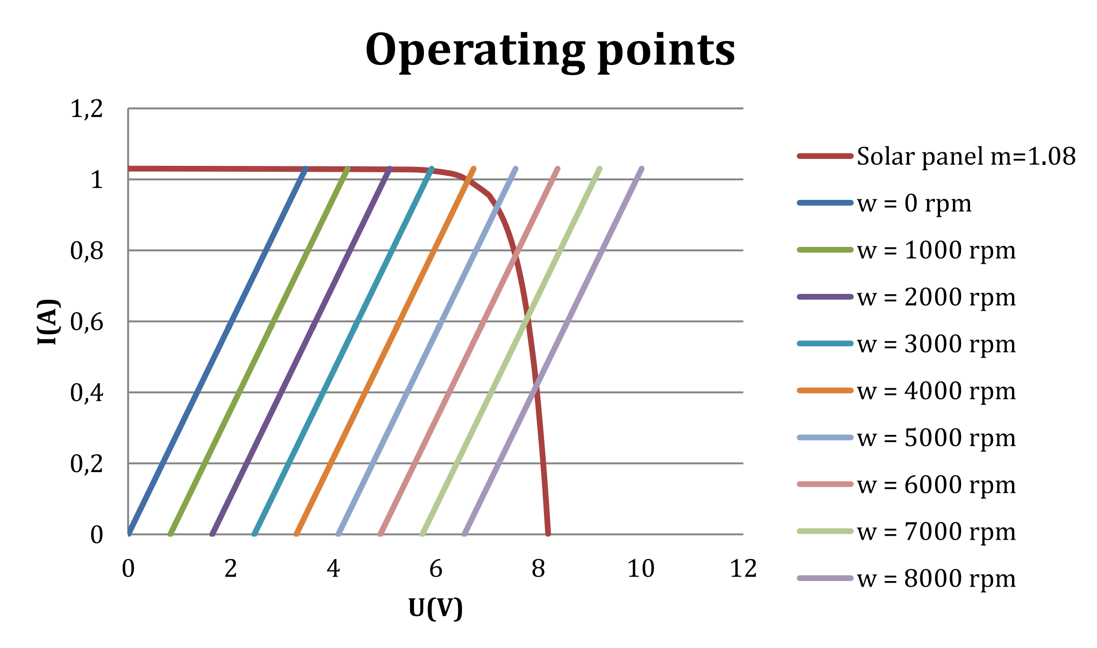


Figure 12: Operating points of the DC- motor

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.

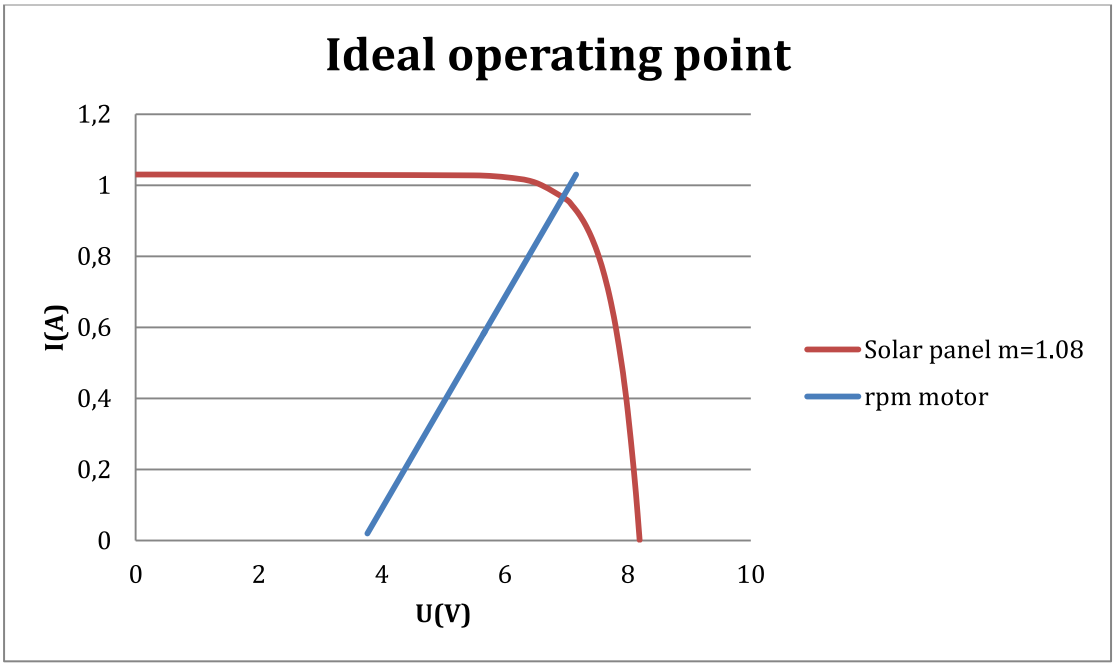


Figure 13: Ideal operating point

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.

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

With:

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

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

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 expect 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.

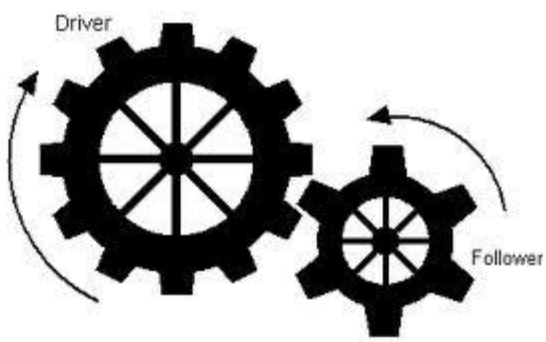


Figure 14: Representation of the gear ratio

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.

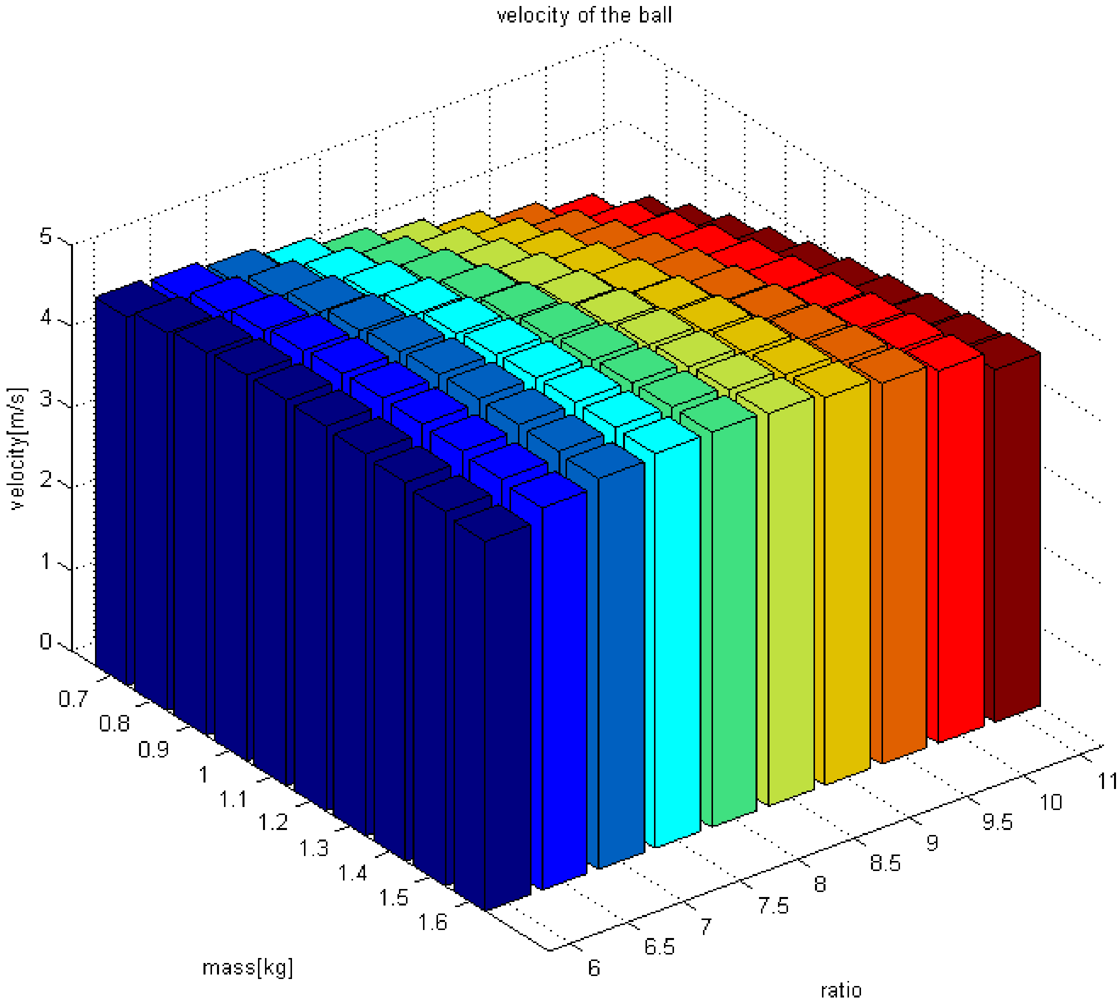


Figure 15: Bar3 plot of speedball matrix

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).

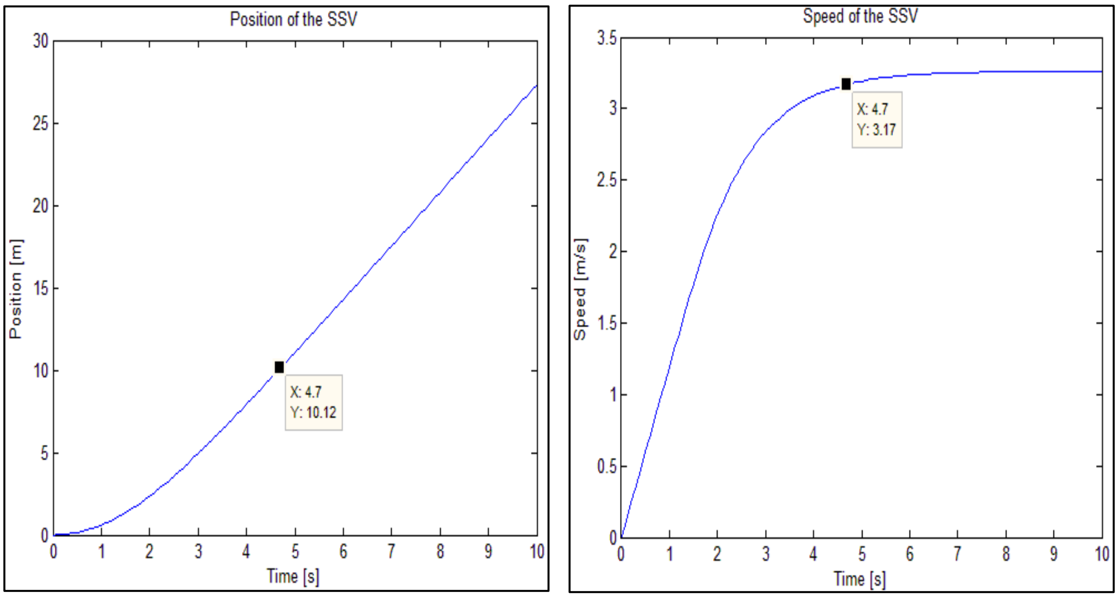


Figure 16: Position and speed of the SSV

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.

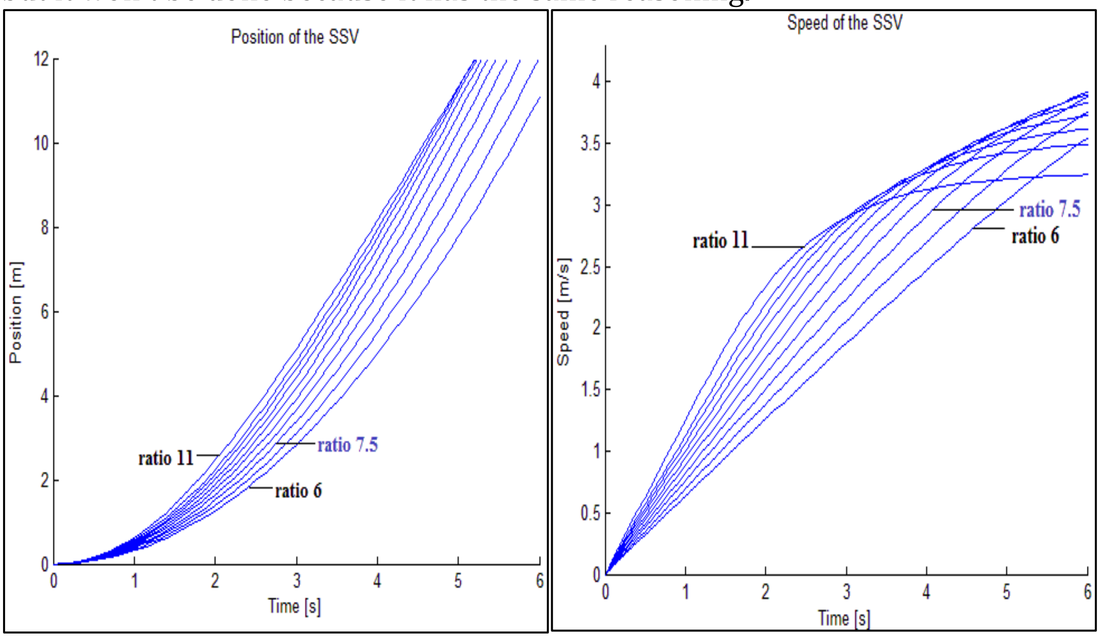


Figure 17: Position and speed of the SSV with various ratios

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.

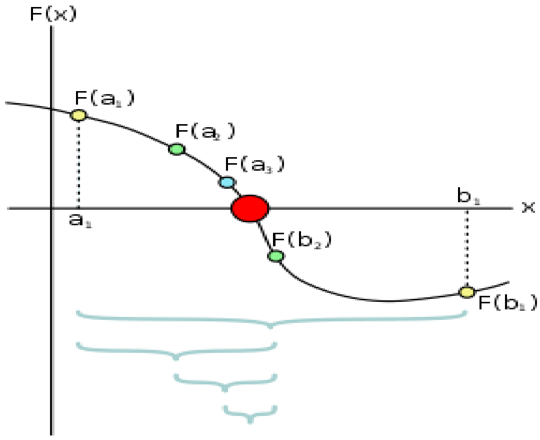


Figure 18: The bisectionmethod

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

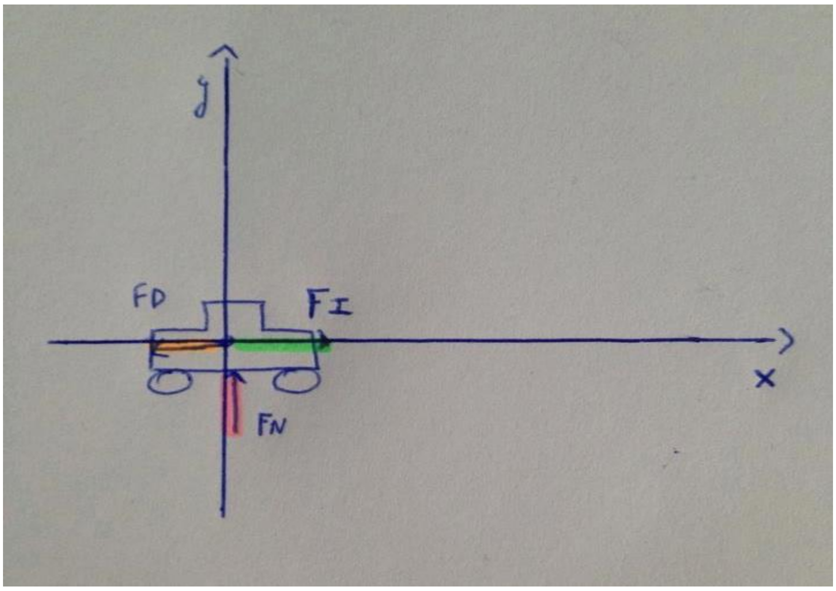


Figure 19: Forces on the SSV

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

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

Normal force F_N = m g

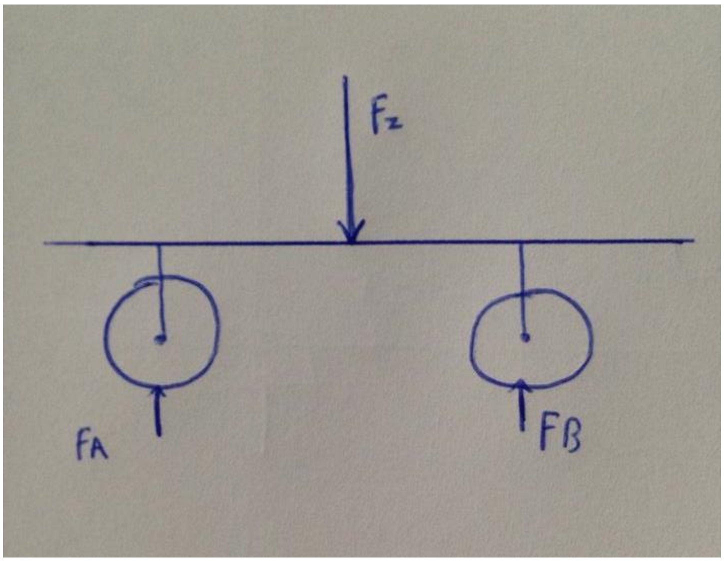


Figure 20: Forces on the wheels

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.

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

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

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) · $\frac{T^2}{2}$ = 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]

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

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

x = 1,05	y(1,05) = -0,47	[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]

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

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.

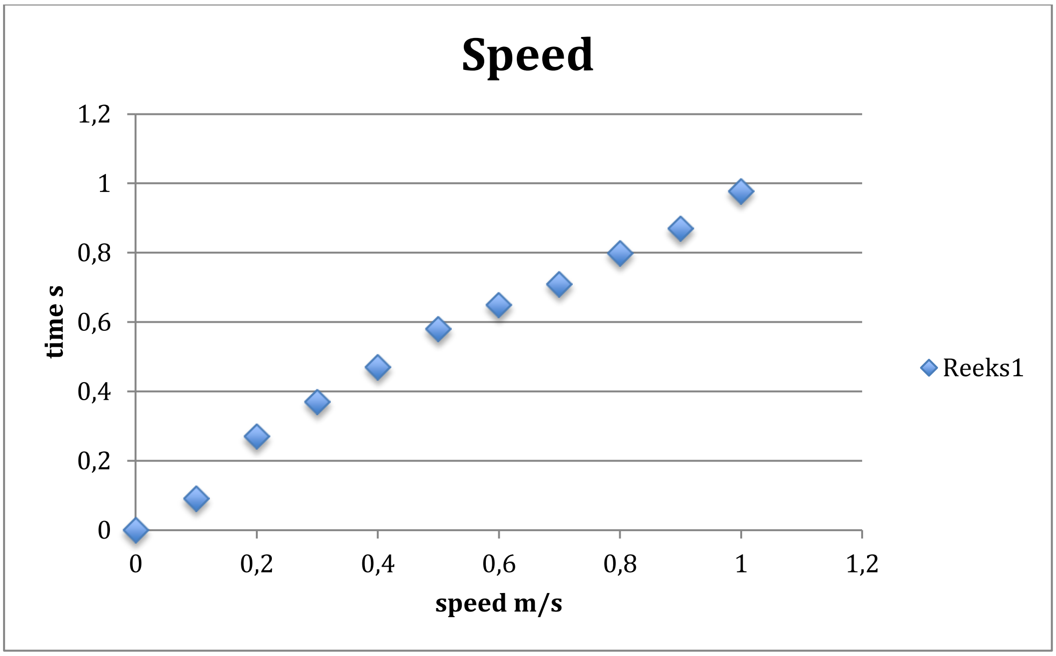


Figure 21: Speed graph constructed with bisection method

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.

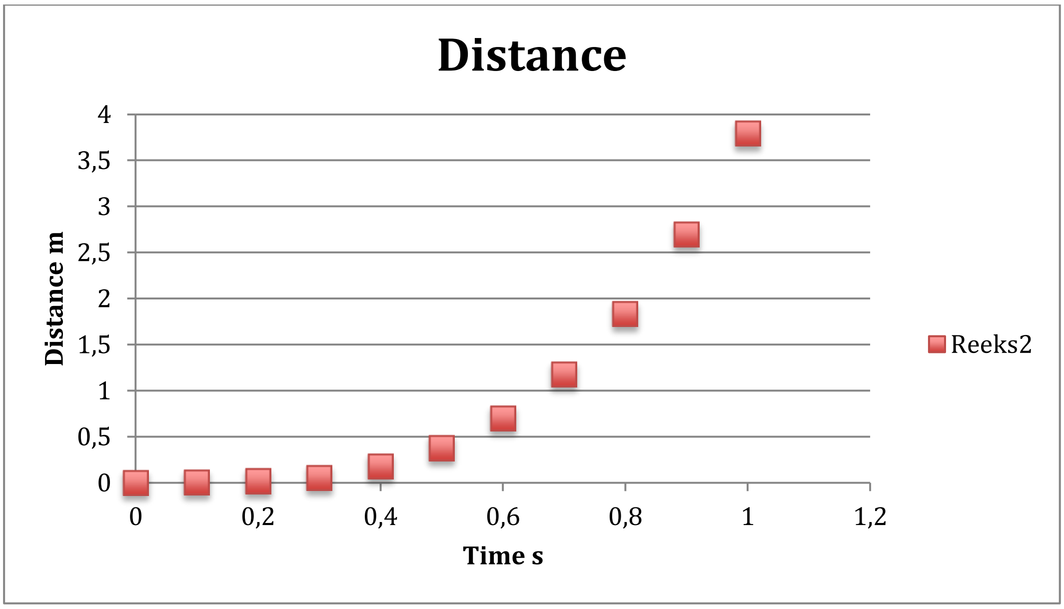
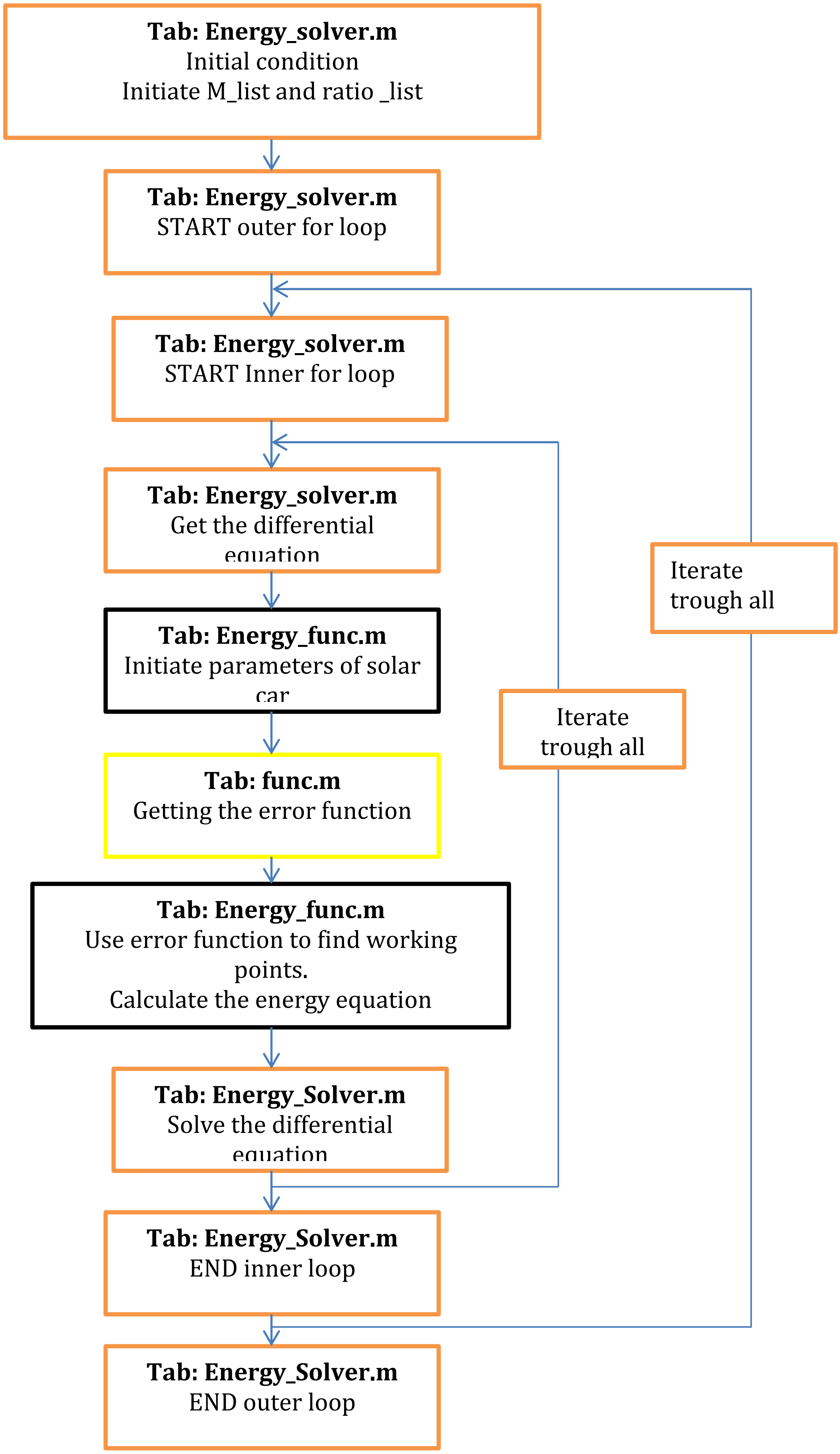


Figure 22: Distance graph constructed with bisection method

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