

Optimizing a solenoid for a Robocup kicker

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Summary

This study, performed for the TechUnited team, continues the research for using a solenoid as a kicking mechanism for Robocup purposes. In a former study, it was found that a solenoid is the most useful option for such a mechanism for a Robocup robot.

A solenoid is a coil that generates a magnetic field. Due to this magnetic field, a force acts on a ferromagnetic projectile, called the plunger, in this magnetic field. This force moves the plunger toward the centre of the coil. This moving plunger can be used to kick the ball. The robot of the team the plunger does not kick directly against the ball, but it uses a lever to kick. Due to restrictions of the Robocup federation, as well as demands of the team, the robot designed in the former study will be optimized. This optimization should result in a robot which works at a lower power level. The solenoid designed previously worked at 30.8 kW, and the aim of this study is to obtain a solenoid working at 3 kW. It also has to fit in the existing TechUnited robot, called the Turtle.

The solenoid designed in this study is tested in a computer program called FEMM. In this program different parameters of the solenoid are studied, like the coil itself, the plunger in it, a shield to get a greater force to the plunger. Geometric properties as well as different materials are investigated.

All results are put together and a solenoid is designed which meets all requirements. The solenoid designed consists of a coil of 16 AWG copper wire, with 2080 turns in 26 layers, a length of 105 mm and an outer radius of 35 mm. The plunger is a solid cylinder of 1020 Steel with a length of 160 mm and a radius of 13 mm. The shield is also made of 1020 Steel and has an axial thickness of 10 mm and a radial thickness of 50 mm.

With these characteristics, the voltage and power required are strongly reduced, and the length of the system is much smaller than the maximal length allowed. However, a lot of research has to be done before the optimal solenoid for the robot is obtained.

Introduction

Since 2005, the University of Technology Eindhoven, together with the University of Technology Delft, participates in the midsize league of the Robocup, under the name TechUnited. Before entering the playfield, a complete robot team had to be built. One of the mechanisms a Robocup robot consists of is a shooting mechanism to kick the ball. A robot of the team, called the turtle, is shown in Fig. 1, which is equipped with a shooting mechanism based on a pneumatic spring.

In a previous study, Cees-Jan Zandsteeg studied different types of shooting mechanisms and found that there are three kinds of major shooting devices: springs, pneumatics and solenoids [1]. In this previous project, properties of the different shooting types, such as shooting power, costs, power modulation etc. were compared. The solenoid was found to be the most attractive option. Based on the requirements and demands of the TechUnited team and Robocup regulations, a solenoid has been designed.

However, the solenoid designed could be improved in several ways. The solenoid works at a very high power level, therefore the efficiency should be studied and a new solenoid has to be designed. It has to be equipped with a controller to make it useful to work with. It also has to be tested to check the predicted parameters.

The aim of this study is to optimize the solenoid, improving its efficiency and decrease the required power. To get an idea of the solenoid's working mechanism, this is first explained in Chapter one. Chapter two handles the requirements that have to be met. In Chapter three the approach of analyzing the solenoids is shown. The optimization is described in Chapter four, which leads to the final design in Chapter five. The conclusions can be found in Chapter six.

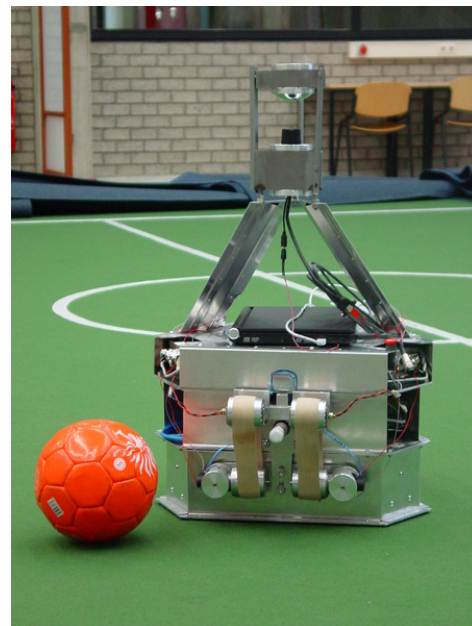


Figure 1: A Turtle

1. Solenoid principle

When a current is sent through a loop of a wire, a magnetic field is build. A solenoid is based on this principle, shown in Fig. 1.1. It contains a lot of loops of wire, forming a coil, producing a magnetic field when an electrical current is send through it.

For a Robocup shooting mechanism, an electromechanical solenoid is found to be the most optimal solution [1]. Electromechanical solenoids consist of a coil wound around a movable steel or iron projectile, called the plunger. The shape of the coil allows the plunger to move in and out of the center. This alters the coil's inductance, which is a measure of the amount of magnetic flux produced for a given electric current. The inductance is dependent of the position of the plunger.

The plunger is used to provide a mechanical force which will be used to kick the ball. The force applied to the plunger by the coil is proportional to the change in current, radius and length of the coil, etc. and will always move the plunger in a direction that increases the coil's inductance.

Solenoids have a typical time constant with a value of L/R , which is the inductance L divided by the electrical resistance R of the coil. The time constant causes a delay in turning the coil on and off. It takes about 5 times the time constant to build up or break down the current required in the coil. So a large time constant means an increase of the reaction time of the solenoid. An example of the current build up or break down is given in Apendix 1.

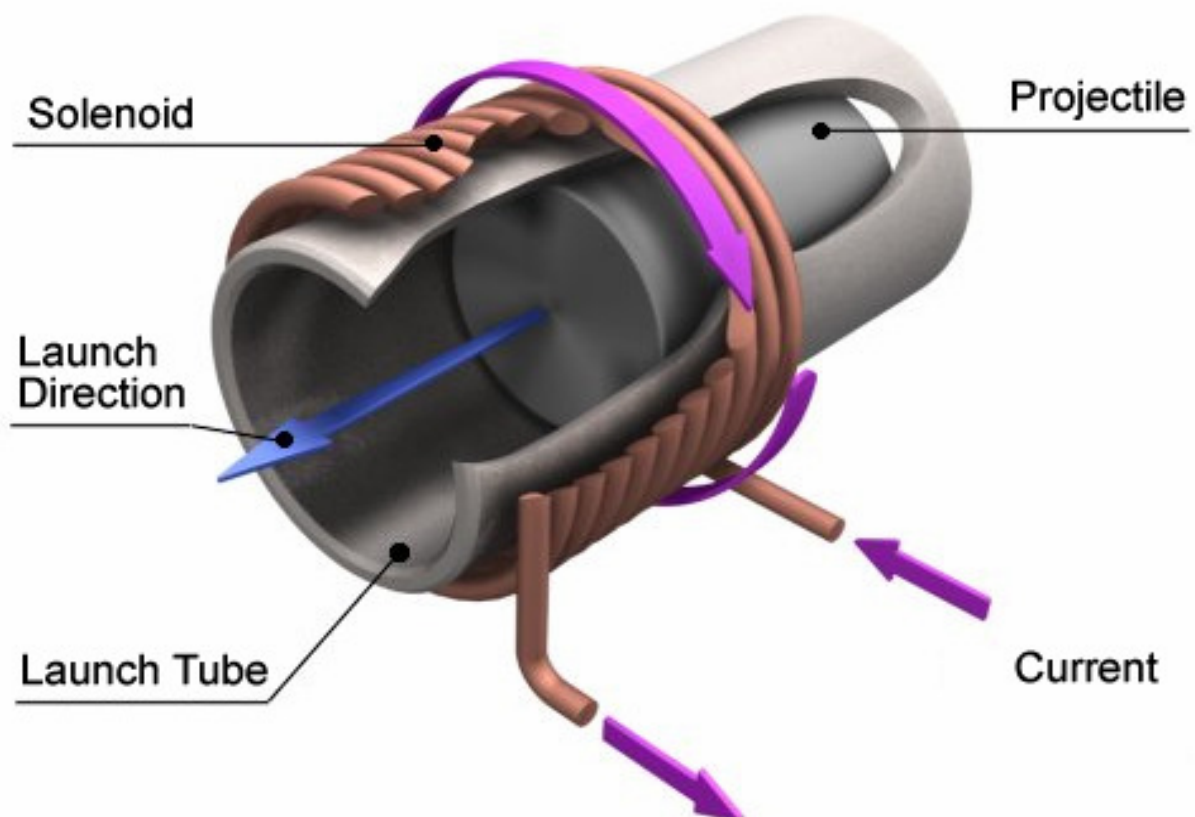


Figure 1.1: A schematic representation of a solenoid

2. Requirements

The solenoid for the Turtle has to meet some requirements. These are restrictions by the Robocup federation as well as demands of the team.

2.1 Transported distance

In the Robocup rules, the size of each midsize league robot player must meet the following criteria [3]:

1. Each robot must possess a configuration of itself and its actuators, where the projection of the robot's shape onto the floor fits into a square of size at least 30 cm × 30 cm and at most 50 cm × 50 cm.
2. Every robot may not have configurations of itself and its actuators, where the projection of the robot's shape onto the floor exceeds a square of size 60 cm × 60 cm.
3. The robot should be in the configuration that fits within the 50 cm × 50 cm square for the majority of play time, in particular when moving around the field, and only occasionally, e.g. when kicking or dribbling, extend to the 60 cm × 60 cm limit.

To fulfill these requirements the solenoid of the previous study, has a transported distance of 100 mm. The solenoid directly hits the ball. Therefore, the robot would instantaneous be 60cm x 50cm during shooting, which is not in violation of the rules.

However the shooting mechanism has been modified. Nowadays the shooting action is performed with a kicking "leg", so the robot can also perform lop balls. This leg can be modeled as a lever, as shown in Fig. 2.1. The leg is a curved strip containing a rotational joint at the top.

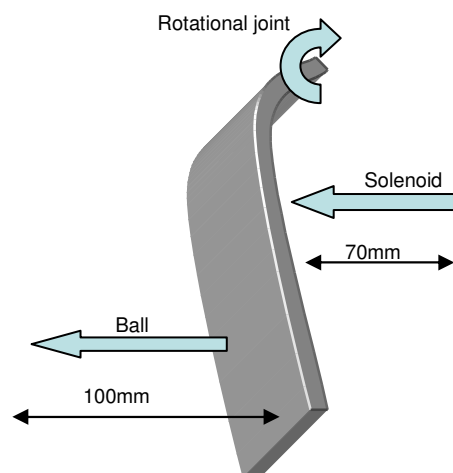


Figure 2.1: Schematic picture of the leg

To fulfill the Robocup rules with this new configuration, the maximum transported distance of the lower end of the leg has to be 100 mm. With the given configuration, this results in a maximum transported distance of the solenoid of 70 mm.

2.2 Energy

A maximum ball speed of 10 m/s delivered by the shooting mechanism is desired. To calculate the energy required from the solenoid, the energy needed to reach a ball speed of 10m/s has been calculated [4]:

$$E_{ball} = \frac{1}{2} m_{ball} v_{ball}^2 + \frac{1}{2} J_{ball} \omega_{ball}^2 \quad (2.1)$$

$$v_{ball} = 10 \left[\frac{m}{s} \right]$$

$$m_{ball} = 0.45 [kg]$$

$$r_{ball} = 0.11 [m]$$

$$J_{ball} = \frac{2}{3} m_{ball} r_{ball}^2 = 3.63 \cdot 10^{-3} [kg \cdot m^2] \quad (2.2)$$

$$\omega_{ball} = \frac{v_{ball}}{r_{ball}} \approx 91 \left[\frac{rad}{s} \right] \quad (2.3)$$

This gives an energy needed:

$$E_{ball} \approx 37.5 [J]$$

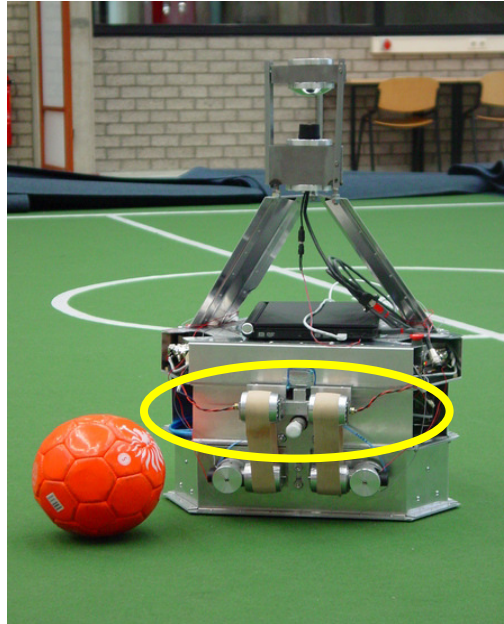
Due to the conservation of energy:

$$E_{solenoid} = E_{ball} = 37.5 [J] \quad (2.4)$$

The friction in the joint, as well as the displacement of the leg is neglected because the leg moves only over a very small angle and the energy consumption of that action is very low.

2.3 Geometry

In the Turtles, only limited space is available for the shooting mechanism. In Fig. 2.2 a Turtle is shown (without the shooting leg). The area shown in the ellipse is reserved for the shooting mechanism.



Picture 2.2: A Turtle

The layer with the shooting mechanism is 95 mm high. The maximum length of the shooting mechanism is 420 mm as shown in the top view of the robot in Fig. 2.3.

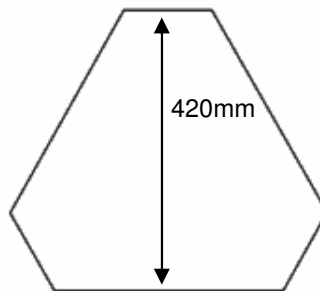


Figure 2.3: Top view of the robot

2.4 Requirements

The solenoid previously designed required a voltage of 450 V and a current of 68 A, which results in a power of 30,6 kW [1]. This high power is very dangerous to work with. To get a solenoid working at a lower power level, a more efficient solenoid has to be designed. Here efficiency stands for the ratio of the power delivered by the plunger divided by the power consumed by the solenoid. The solenoid in this study is chosen to have a maximal value of 3 kW, reducing the power by about factor 10. In this study the current is chosen to be 20 A at maximum and the voltage is 150 V at maximum. The reason why the current is more reduced than the voltage is because the heat production in the coil is more dependent on the current.

All requirements are shown in table 2.1.

Table 2.1: requirements for the solenoid

Specifications	Zandsteeg [1]	This study
Ball speed [m/s]	10 m/s	10 m/s
Energy [J]	37.5 J	37.5 J
Transported distance [mm]	100 mm	70 mm
Length [mm]	200 mm	420 mm
Diameter [mm]	31 mm	95 mm
Power [W]	30600 W	3000 W
Current [A]	68 A	20 A
Voltage [V]	450 V	150 V

3. Approach

Only one solenoid will finally be designed. However, various options and parameters are evaluated.

3.1 FEMM

To model and analyze the designed solenoids a finite element method program called Finite Element Method Magnetics (FEMM) is used. In FEMM, 2-dimensional and axis-symmetric time independent problems can be solved. The program uses Maxwell equations combined with finite element method. For a more detailed explanation of the FEMM solving method, see [1].

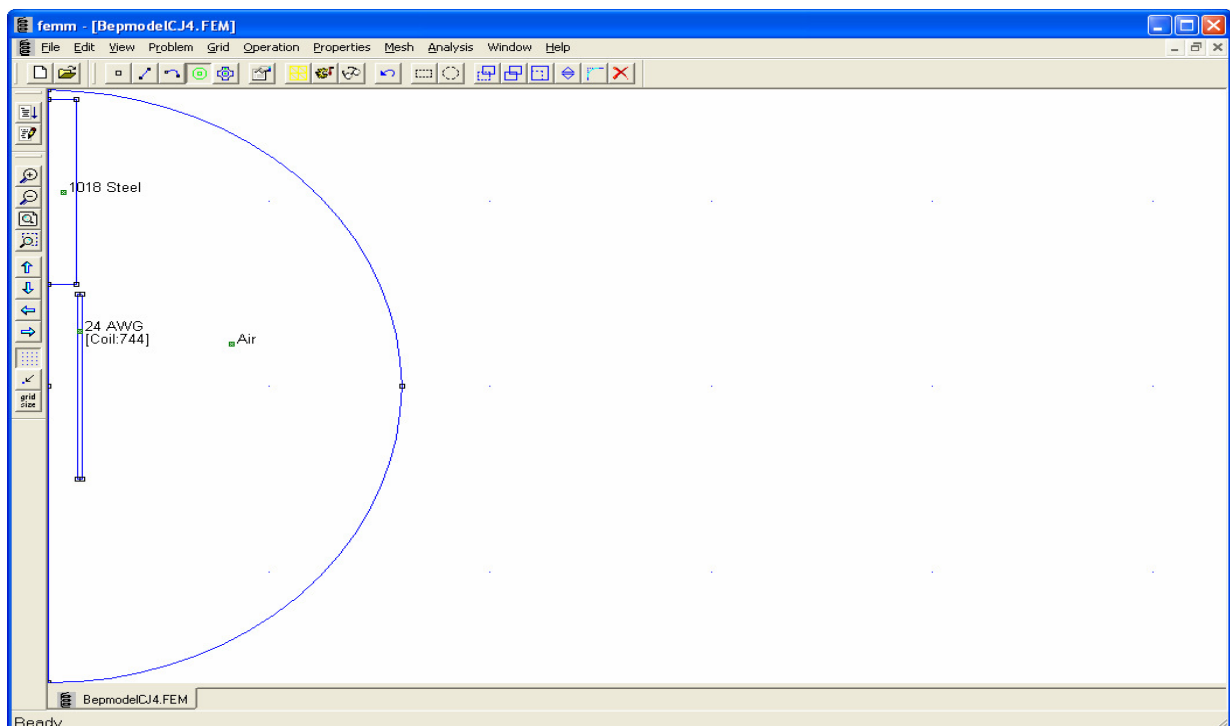


Figure 3.1: The FEMM interface

The interface of FEMM is shown in Fig. 3.1. In this figure, a solenoid is drawn in the axis-symmetric solver. By placing nodes and connecting them by lines, closed surfaces are made in FEMM. It is possible to create almost every surface. Different properties such as material properties, circuit properties (in case of the coil), geometric properties, boundary conditions and mesh conditions can be attached to these surfaces.

The program contains a library of common used materials. Winding wires, ferromagnetic materials, air properties, B-H curves, different boundary conditions and many other relevant parameters are stored in it [6].

3.2 Mesh size

To analyze and solve a model, a mesh has to be created. This mesh is a sort of web of little triangles, which are necessary for the finite element method. In Fig. 3.2 a meshed model is shown.

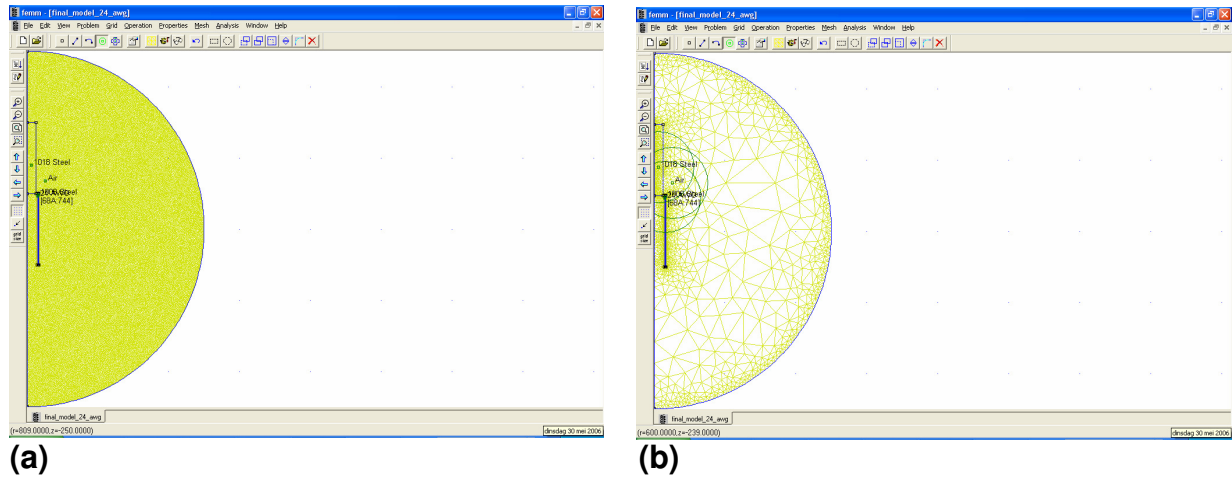


Figure 3.2: A model meshed in FEMM, (a) small mesh size, (b) large mesh size

The size of the little triangles is called the mesh size. A larger mesh size means larger triangles and therefore a reduced number of triangles for a given size model. This results in a shorter calculation time, but also in a less accurate calculation. In Fig. 3.2, both small and large mesh sizes are shown. For the models used in this study, it is necessary to analyze the models as accurate and as quick as possible. Therefore, a test is performed to determine the optimal mesh size. A model has been made and it is tested with a small mesh size (0.25) and a large mesh size (5) and many sizes between these two, in very small steps. The results of the tests were not very different from each other, in fact the results of mesh size 0.25 and 5 differed not even 1%. But the calculation time changed very much, as shown in Fig. 3.3.

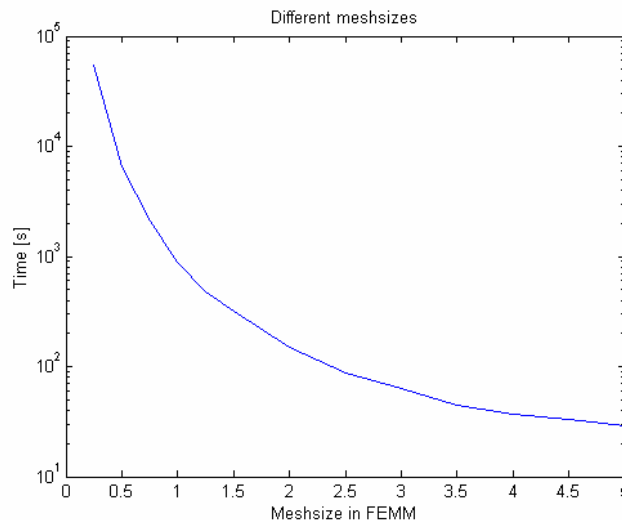


Figure 3.3: Mesh size versus calculation time

The calculation time at the mesh size of 0.25 is 14:37:30 hours, which is 52650 seconds. The calculation time at the mesh size of 5 is only 38 seconds. Therefore, a mesh size of 5 for the future models was chosen.

3.3 Energy calculation

FEMM knows the B and H values of the materials used, which are parameters related to the magnetic behaviour of the material. Therefore, FEMM can calculate the magnetic field energy W_c with the following equation [6]:

$$W_c = \int \left(\int_0^H B(H') dH' \right) dV \quad (3.1)$$

After calculating the co-energy at several positions of the plunger in the coil, the solenoid force at these positions can be estimated with the following equation:

$$F = \frac{W_c(x + \delta) - W_c(x)}{\delta} \quad (3.2)$$

Where x denotes the initial position, $x + \delta$ denotes the perturbed position, and δ is the magnitude of the perturbation. The force F determined in this way acts along the direction of the perturbation.

The parameter needed is the energy absorbed by the plunger. First, in FEMM the solenoid force is calculated at n positions. Now the energy is calculated with the following equation:

$$E_{solenoid} = \sum_{i=1,2,\dots}^n F(x_i) \Delta_i \quad (3.3)$$

With $F(x_i)$ the force at position x_i and Δ_i the distance to the following position in which the force is calculated.

3.4 Lua scripts

In FEMM, it is possible to create script files. These have to be written in the programmer language lua. With these script files it is possible to give commands to FEMM, and for example modify and analyse the models. So when a lot of calculations on the same model have to be done, such scripts are very useful files. In this case, the energy delivered by the solenoid has to be known, therefore it is necessary to know the force applied by the solenoid at several positions. Furthermore a lot of properties have to be analysed. So in this case a lot of lua scripts are used. In Apendix 2 at page 30 a lua script example is given. This script changes the position of the plunger in a model and calculates the solenoids force at

all the given positions. It also puts the results in a text file so the results can be used later on. Explanation of the script is entered in the script after the -- signs.

3.5 Data processing

To obtain the energy data to see if the solenoids meet the requirements, the FEMM outputs are imported in excel. In excel the data is processed to obtain graphics and to know the energy delivered by the solenoid in one stroke.

To get an overview, the whole approach is presented in Fig. 3.4.

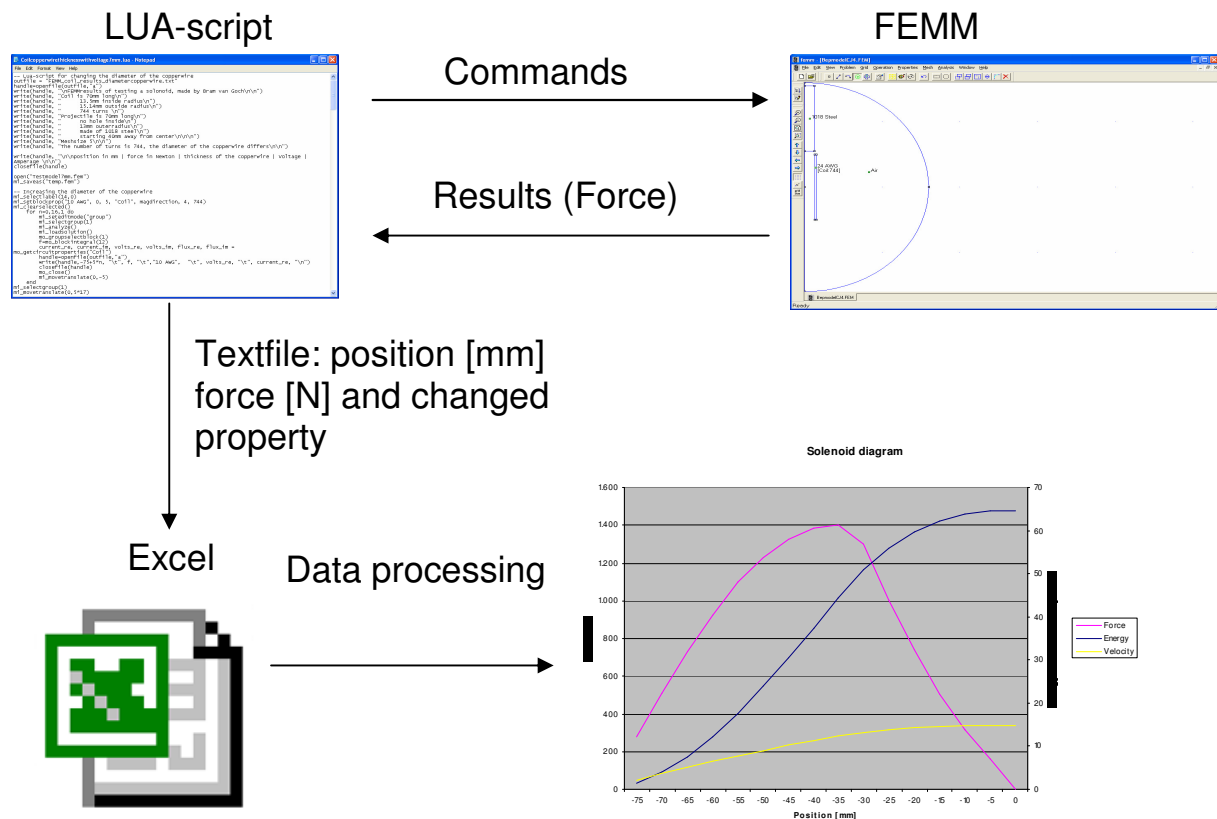


Figure 3.4: The approach

4. Optimization

To design a new solenoid, several parameters are studied in this study. In this chapter all the investigated parameters are optimized.

4.1 Solenoid

To optimize the solenoid, it is useful to first look at the aspects of the solenoid. To make this something easier, a schematic figure of a solenoid is shown in Fig. 4.1.

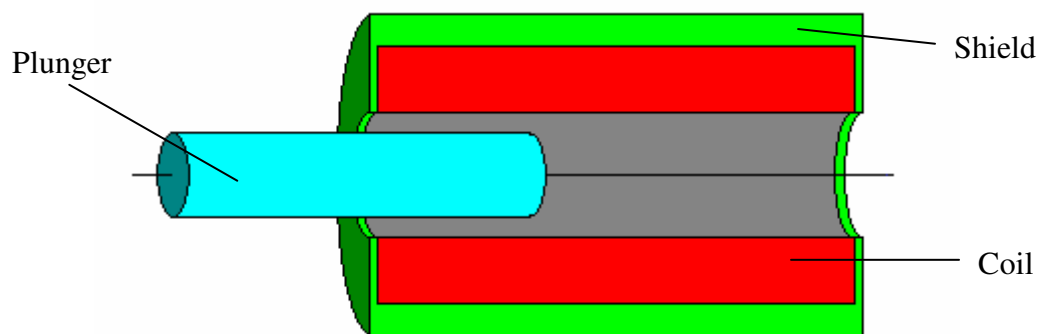


Figure 4.1: Schematic solenoid

The solenoid mainly consists of 3 parts: the plunger, the shield and the coil. The plunger is the movable part which delivers the force to the leg.

The shield makes sure that the magnetic field doesn't influence other systems in the robot, like the motors or the laptop and also makes sure that the other systems don't influence the magnetic field built by the coil.

The shield also decreases the reluctance at the outer positions of the solenoid. Where reluctance is like electric resistance, the higher the reluctance of a material, the more energy is absorbed by this material. So to be sure most energy will be available inside the coil, the reluctance outside the coil has to be as little as possible. The reluctance of a steel shield is much less than the reluctance of air. So the shield makes the solenoids also more efficient.

The coil is necessary to build the magnetic field.

To get the most efficient solenoid, all three parts of Fig. 4.1 have to be optimized. There are a lot of properties which can be optimized. In this study, the properties examined are:

- Plunger: length, inner and outer radius, material, other geometric aspects
- Shield: material, thickness
- Coil: length, layers, turns, wire thickness

4.2 Plunger

4.2.1 Plunger length

First the parameters of the plunger are analysed. The length of the plunger is the first parameter investigated. For every length of the plunger, the energy delivered by the solenoid is calculated, which is shown in Fig. 4.2.

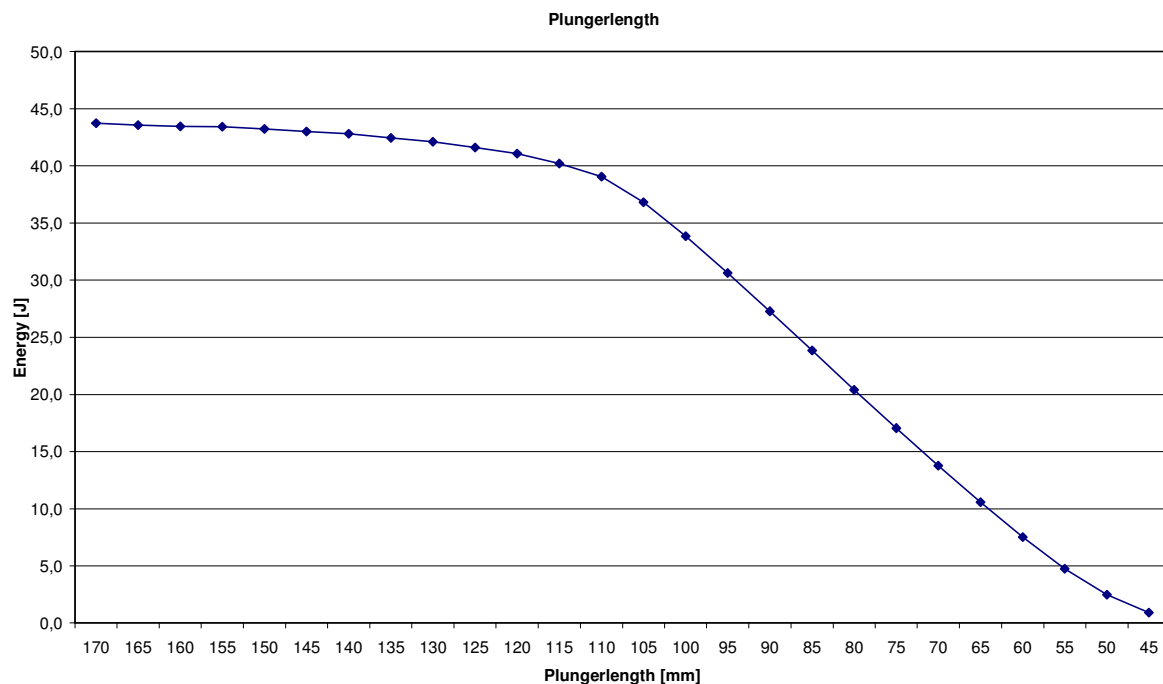


Figure 4.2: Plunger length versus the energy

On the x-axis, the plunger length in mm is given, decreasing from 170mm to 45mm. It can be seen that a longer plunger absorbs more energy than a short one, which means that it also delivers more energy due to the conservation of energy. The explanation for this is the fact that a longer plunger has a greater appearance in the magnetic field and thus absorbs more magnetic energy.

The graph goes asymptotic when the plunger is longer than 110 mm. This is because above a certain length, the extra length moves in an area far outside the coil, where the magnetic field is almost zero and very little extra energy is delivered to the plunger.

4.2.2 Plunger radii

The next properties of the plunger analyzed are the radii of the plunger. The outer radius as well as the inner radius is investigated. The outer radius is the radius of the cylinder. The inner radius is the radius of the hole when using a hollow cylinder. So when looking at the inner radius, it is investigated whether a hollow cylinder is more efficient than a solid one. The two radii are shown in the Fig. below.



Figure 4.3: Inner (a) and outer (b) radius of the plunger

The energy dependencies of the two radii are plotted in Fig. . In this case the inner radius of the coil is 13.5 mm. Varying the inner radius of the plunger, the outer radius of the plunger is kept constant at 13 mm. Varying the outer radius of the plunger, the plunger is a solid cylinder.

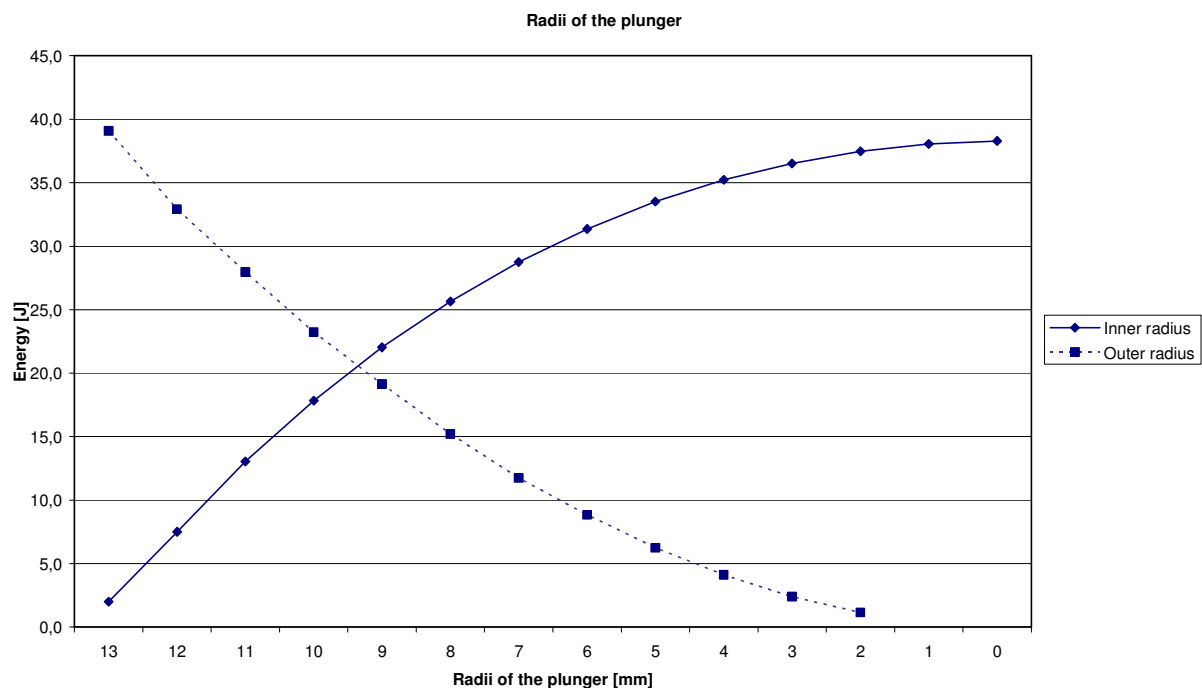


Figure 4.4: The radii of the plunger versus the energy

Out of Fig. 4.4 two conclusions can be drawn. First, the inner radius has to be as small as possible to get the most energy. A solid cylinder is the most efficient plunger type.

Second, the outer radius has to be as large as possible to get the most energy. This implies that the gap between the coil and the plunger has to be as small as possible. This is because air has a high reluctance and the smaller the gap, the less energy is absorbed by the air and the more energy is available for the plunger to absorb. The outer radius of the plunger will be 13 mm.

4.2.3 Plunger material

A lot of materials can be used for the plunger. There are a lot of ferromagnetic materials. Therefore, a model is used in which the energy delivered by the solenoid is calculated for the different materials. The results are presented in Fig. 4.5.

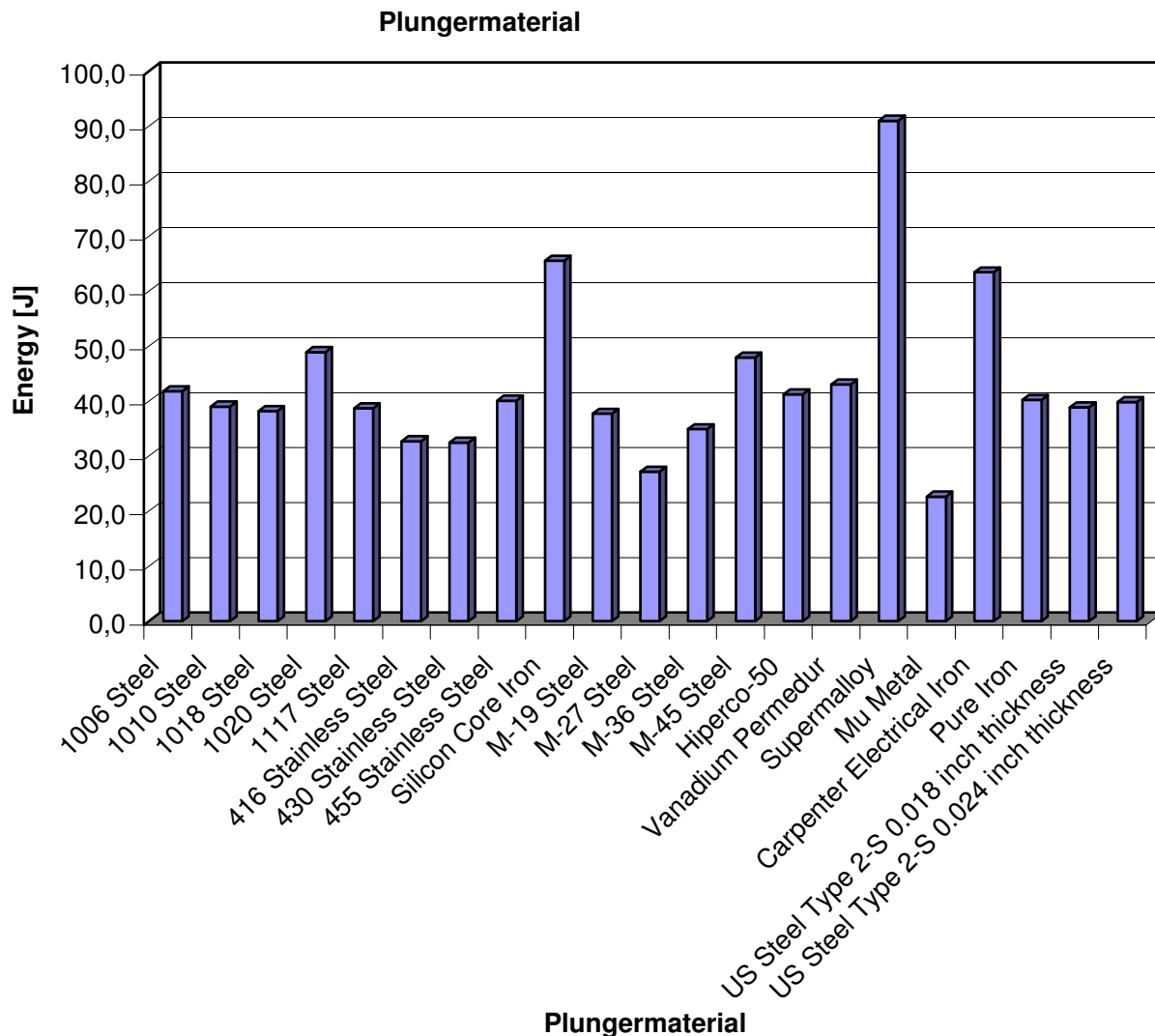


Figure 4.5: The material of the plunger versus the energy

Three materials are most attractive to use for the solenoid: Supermalloy, Silicon Core Iron and Carpenter Electrical Iron. However these materials are all three very difficult to get. So it is no option to use these materials. From the other materials left, 1020 Steel is the best option, can be seen. For the solenoid, 1020 Steel will be used.

4.2.4 Plunger geometry

The plunger will have a cylindrical shape, as described in section 4.2.2. No hollow cylinder is used, but perhaps holes at the end or a bulging end of the cylinder, as drawn in Fig. 4.6, will increase the efficiency of the solenoid. This was investigated, but a hole did not affect the efficiency positively. Only the elongation which is involved with a bulging end has little positive effect, but an elongation of the cylinder with the same length has a larger effect. A bulged end has a greater air gap than a cylindrical elongation, so less energy is stored in the plunger. Therefore there will be no holes at the end of the cylinder or a bulged end. The plunger will be a long solid cylinder, with no holes, made out of 1020 Steel.

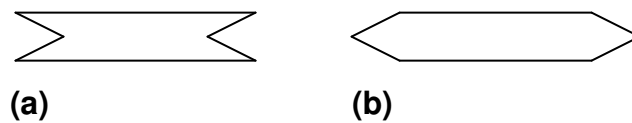


Figure 4.6: axial intersection of plungers with holes (a) and bulged ends (b)

4.3 Shield

4.3.1 Shield material

Only two properties of the shield are considered in this study, the material and the thickness. First the material of the shield is studied. For the material of the shield a similar test is performed as the test for the material of the plunger. The results are given in Fig. 4.7 below.

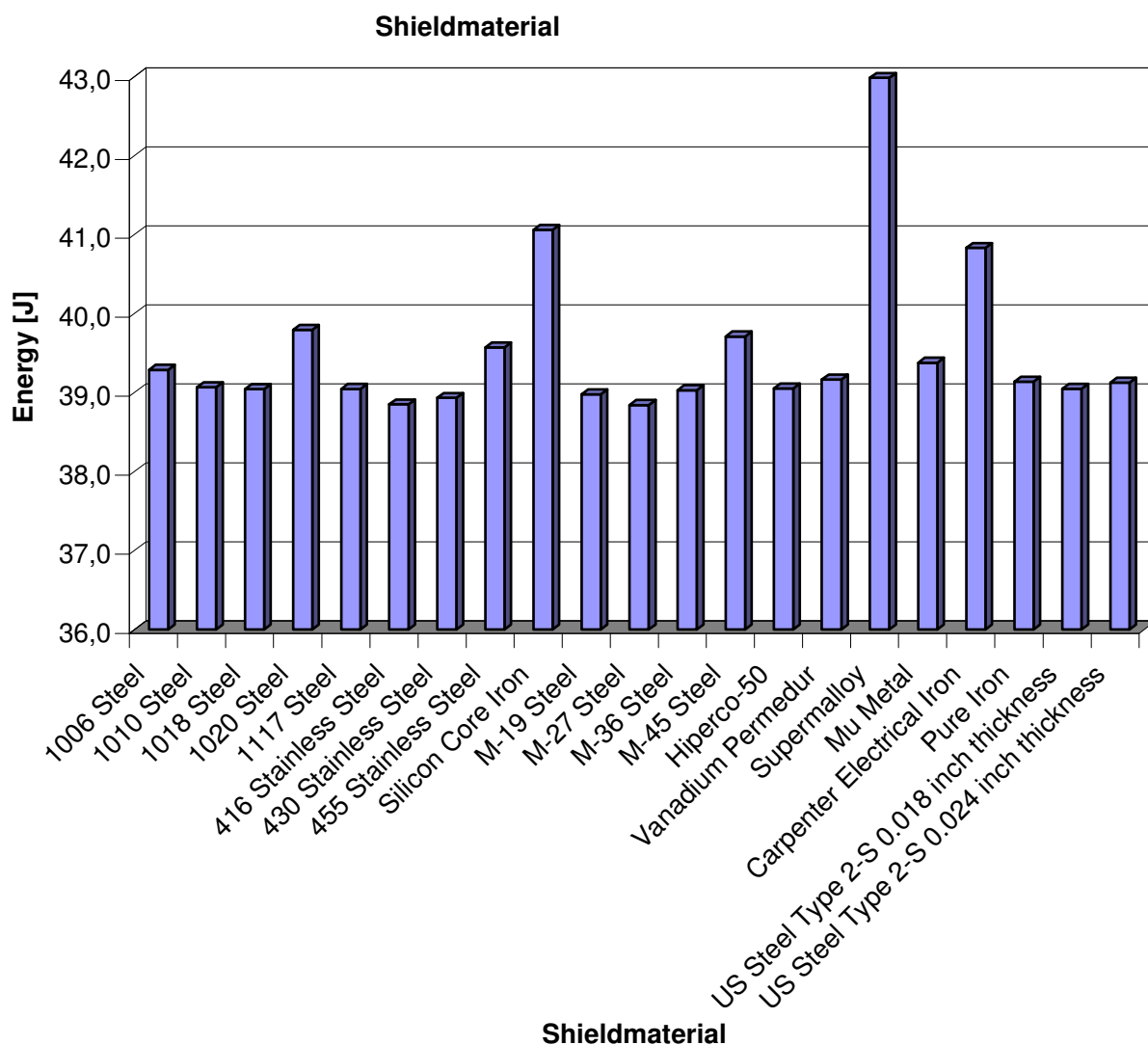


Figure 4.7: The material of the shield versus the energy

Here the same conclusion can be drawn as for the material of the plunger. Supermalloy, Silicon Core Iron and Carpenter Electrical Iron are the best options. However because of the low availability those three are put aside and the fourth best option is chosen, 1020 Steel.

4.3.2 Shield thickness

The second property of the shield analyzed is the thickness of the shield. First, some insight in the reluctance theory of a coil is required. This reluctance theory is similar to the theory of the resistance in an electric scheme, using the following equivalents.

- The equivalent to resistance is reluctance, \mathfrak{R} .
- The equivalent to current is flux, F .
- The equivalent to voltage is magneto motive force (mmf), M .

An axis-symmetric representation of a solenoid with a shield is shown in Fig. 4.8, where the line at the bottom of the picture is the symmetric axis. Herein the dotted line is a field line of the magnetic field. In this figure, 1 represents the plunger, while 2 and 4 are the axial parts of the shield. 3 stands for the radial part of the shield. Each part has it's own reluctance. This is schematically given right beside the arrow in the figure.

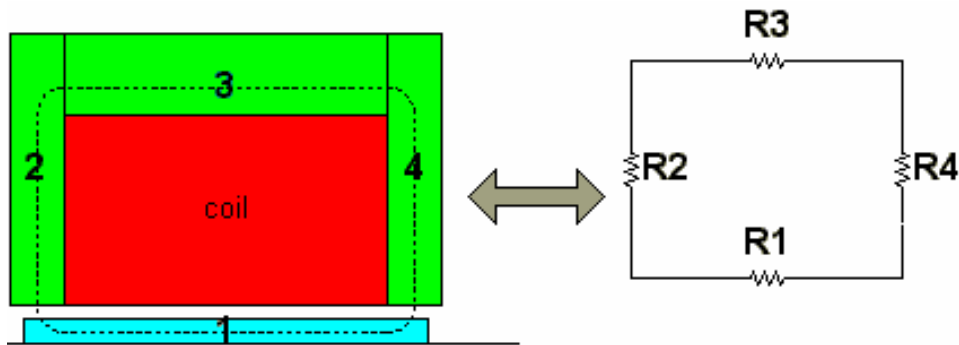


Figure 4.8: An axi-symmetric solenoid with the reluctance interpretation

For electric circuits holds:

$$I = \frac{U}{R} \quad (4.1)$$

In which I is the current, U the voltage and R the resistance. For magnetic circuits holds:

$$F = \frac{M}{\mathfrak{R}} \quad (4.2)$$

The reluctance \mathfrak{R} is defined as [1]:

$$\mathfrak{R} = \frac{l}{A_c} \cdot \frac{1}{\mu} \quad (4.3)$$

The length l is the length of the path of the magnetic field line given by the dotted line in Fig. 4.8. The cross-section A_c is the area where the field runs trough and μ is a material parameter called the permeability, which has to be high for a low reluctance. This parameter is the best for 1020 Steel as described in the previous section.

Because the coil is not changed when adding a shield, the total reluctance of the total system is:

$$\mathfrak{R}_{total} = \mathfrak{R}_1 + \mathfrak{R}_2 + \mathfrak{R}_3 + \mathfrak{R}_4 \quad (4.4)$$

The flux and magneto motive force do not change, because they only depend on the coil. Eq. 4.2 shows that the total reluctance also does not change.

For most of the energy to be absorbed by the plunger, the reluctances of 2, 3 and 4 have to be as low as possible, according to (4.4). From (4.3) it can be seen that the thicker the shield, the greater the cross-section and the more efficient the solenoid.

A thick shield of 1020 Steel has to be designed. The size is limited by the height requirement as described in Chapter 2, in combination with the thickness of the coil, which will be discussed in section 4.4. In section 4.4 the final shield thickness will be given.

4.4 Coil

The coil has many parameters to modify, like the number of turns, the length, the number of layers, the wire thickness.

4.4.1 Turns

First the number of turns is examined. Eq. 4.5 calculates the magnetic field intensity inside a coil, or vector H [11]:

$$H = \frac{NI}{4b} \left[\frac{x+b}{\sqrt{(x+b)^2 + a^2}} - \frac{x-b}{\sqrt{(x-b)^2 + a^2}} \right] \quad (4.5)$$

With the number of turns N , current I , half the length of the coil b , radius a and position in the coil x , with $x = 0$ at the centre of the coil. Out of (4.5), it seems that the more turns in a coil, the stronger the magnetic field. A stronger field results in a greater force to the plunger and therefore more energy will be absorbed by the plunger in this study. When adding more turns, the length or the radius or both will increase. These aspects will be analysed in the next sections.

There is also a negative aspect related to a higher number of turns. More turns will increase the time constant of the coil, as can be seen in (4.6) till (4.10). This results in an increase of the reaction time of the coil and a longer time to control the coil (see Appendix 1).

The equation for the inductance of a coil and the resistance of a coil are [1]:

$$L = \frac{0.0315 \cdot N^2 \cdot \left(\frac{R_1 + R_2}{2} \right)^2}{6 \cdot \frac{R_1 + R_2}{2} + 9 \cdot l_{coil} + 10 \cdot (R_2 - R_1)} \quad (4.6)$$

With R_2 the outer radius, R_1 the inner radius, N the number of turns and l_{coil} the length of the coil. The resistance of the coil is [1]:

$$R_{coil} = \rho \cdot l_{wire} \quad (4.7)$$

With ρ the resistance per unit length, where the AWG number still has to be chosen, out of Appendix 3 at page 31 and l_{wire} can be calculated with [1]:

$$l_{wire} = 2\pi \left(R_2 + \frac{(R_2 - R_1)}{2} \right) \cdot N \quad (4.8)$$

With R_2 the outer radius, R_1 the inner radius and N the number of turns. The time constant can now be calculated with [1]:

$$\tau = \frac{L}{R_{coil}} \quad (4.9)$$

When substituting Eq. 4.6, 4.7 and 4.8 in 4.9, gives:

$$\tau = \frac{0.0315 \cdot N \cdot \left(\frac{R_1 + R_2}{2} \right)^2}{6 \cdot \frac{R_1 + R_2}{2} + 9 \cdot l_{coil} + 10 \cdot (R_2 - R_1)} \cdot \frac{1}{\rho \cdot 2 \cdot \pi \left(R_2 + \frac{(R_2 - R_1)}{2} \right)} \quad (4.10)$$

In (4.10) τ increases linear with the number of turns N . But when a coil has more turns, it has more layers or is longer. The radii and the length are also parameters in (4.10). Therefore these are studied in the next sections.

4.4.2 Layers

When increasing the number of layers at a position, the magnetic field intensity in the coil at that position increases too, seems out of (4.5). But due to the increasing number of layers, the outer radius of the coil also increases. With the increasing number of turns and the increasing outer radius the time constant also increases. In this study it is found that 26 layers, working at 20 A, deliver enough energy to meet the energy requirements of Chapter 2.

4.4.3 Length

The length of the coil can be changed in two different ways. First, the number of turns can be kept constant. When the coil is made longer, fewer layers are present. Second, the number of turns per length can be kept constant. In this case, a longer coil contains more turns. The first option results in a less strong coil at all positions in the coil according to (4.5). But the force acts over a larger distance, the time constant decreases.

The second option results in a coil that has a larger distance where the force stays the same. This force does not increase or decrease. Due to the elongation of the coil the number of turns increases, which results in a higher time constant. This relation implies that, when keeping the coil at 26 layers, the coil does not have to be very long. The length has to be appropriate to maintain the force while making the 70 mm stroke.

4.4.4 Wire thickness

When keeping the inner radius of the coil constant, the thickness of the copper wire of the coil has no influence on the force applied by the coil. This can be seen in (4.5). However the wire thickness influences an other parameter of the coil, the resistance.

The resistance of Eq. 4.7 can be influenced by the wire thickness. In Appendix 3 it is shown that using a thicker copper wire decreases the resistance per unit length. This results in a lower resistance. Because the current is kept the same, but the resistance decreases when using a thicker wire, the voltage decreases according to Ohm's law (Eq. 4.1). To get a better idea of how these two values depend on each other, in Fig. 4.9 the two are plotted against each other, in a standard coil model. A negative aspect of a thicker wire is that the time constant increases.

When choosing the optimal wire thickness, the height restriction out of Chapter 2 and the number of layers and the thickness of the shield are all connected by the following relation:

$$2 \cdot (R_1 + n \cdot d_{\text{wire}} \cdot w + s) = y_{\text{max}} \quad (4.11)$$

Here, R_1 is the inner radius of the coil, n the number of layers, d_{wire} the diameter of the copper wire, w the windingfactor, s the radial thickness of the shield (number three in Fig. 4.8) and y_{max} the maximum height. In this study the parameters chosen are d_{wire} : 1.29 mm which is 16 AWG. The radial thickness of the shield is set to be 10 mm.

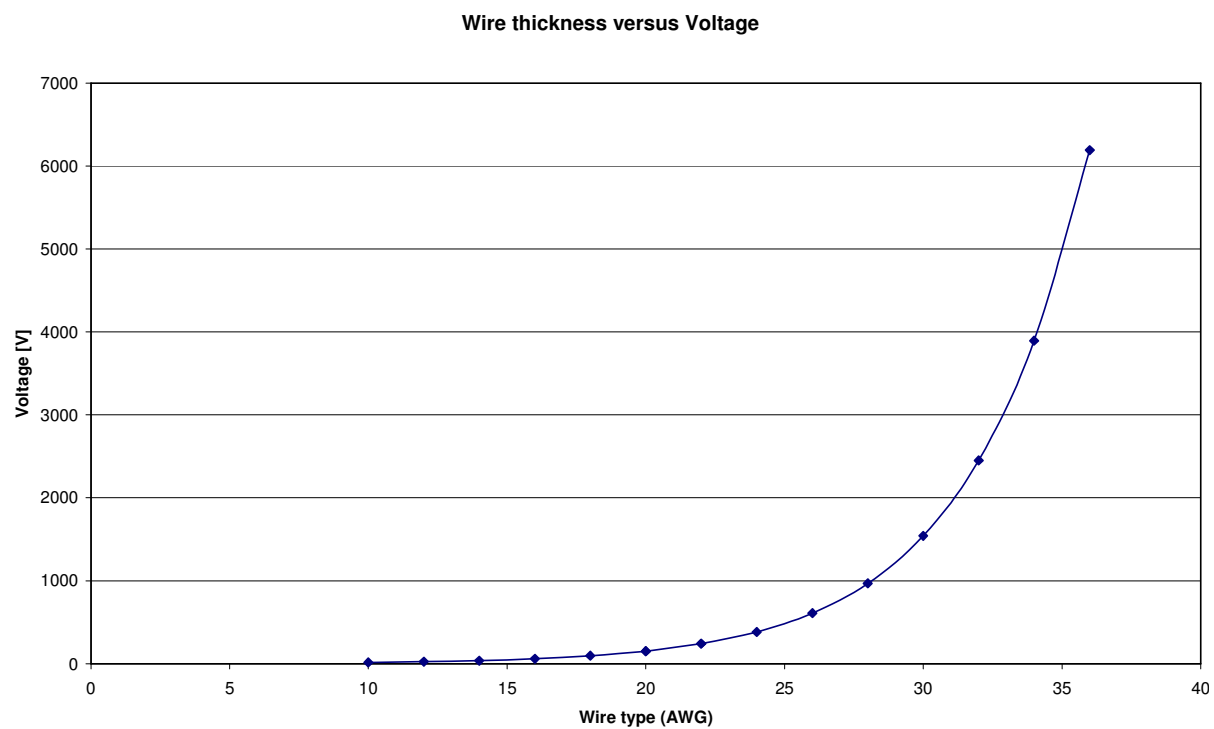


Figure 4.9: The wire thickness versus the voltage

5. Final design

After analyzing all parameters, the final design for the solenoid could be made.

5.1 Final parameters

The values of all parameters are presented in table 5.1 and visualised in Fig. 5.1.

Table 5.1: Final solenoid design

Coil	
Length	105 mm
Inner radius	13.5 mm
Outer radius	35 mm
Wire type	16 AWG
Turns	2080
Layers	26
Shield	
Material	1020 Steel
Radial thickness	10 mm
Axial thickness	50 mm
Plunger	
Length	160 mm
Radius	13 mm
Material	1020 Steel

The radial thickness is the thickness of the shield radially connected to the coil (see number 3 in Fig. 4.7). The axial thickness is axially connected (2 and 4 in Fig. 4.7).

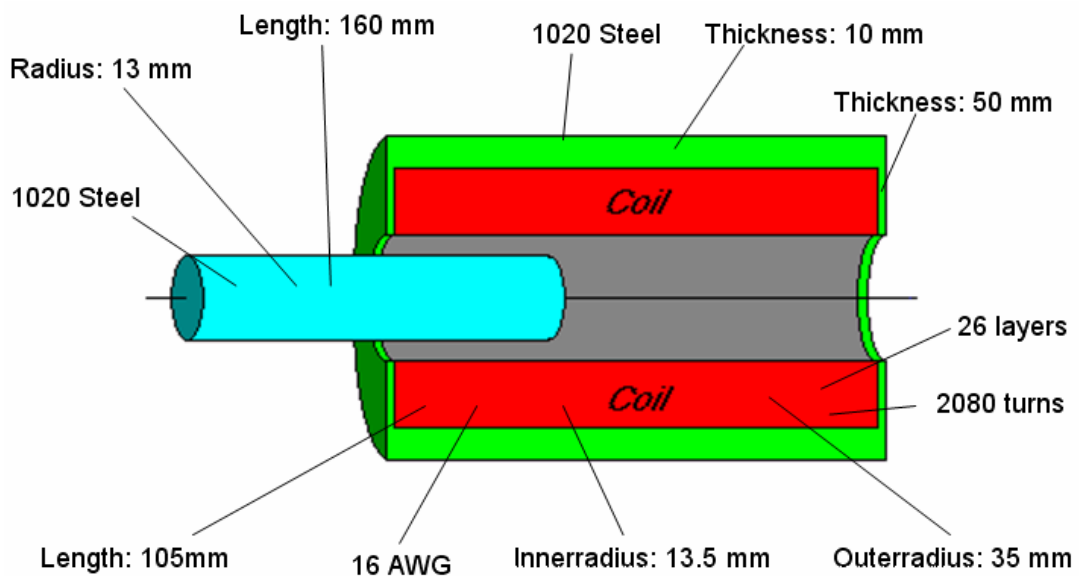


Figure 5.1: Final solenoid design

5.2 Transported distance

The force versus position characteristic of the solenoid designed is given in Fig. 5.2, using a current of 20A. The position is the position of the centre of the coil versus the centre of the plunger. This position is negative because the plunger is located at the back of the coil to be pulled inwards. The transported distance allowed in the design is 70 mm according to the requirements. Out of Fig. 5.2 the 70 mm with the highest force is taken to obtain the most energy absorbed by the plunger. These 70 mm are -105 till -35mm and given between the two vertical lines in the figure. This implies that the optimal stroke of the plunger is performed in that area.

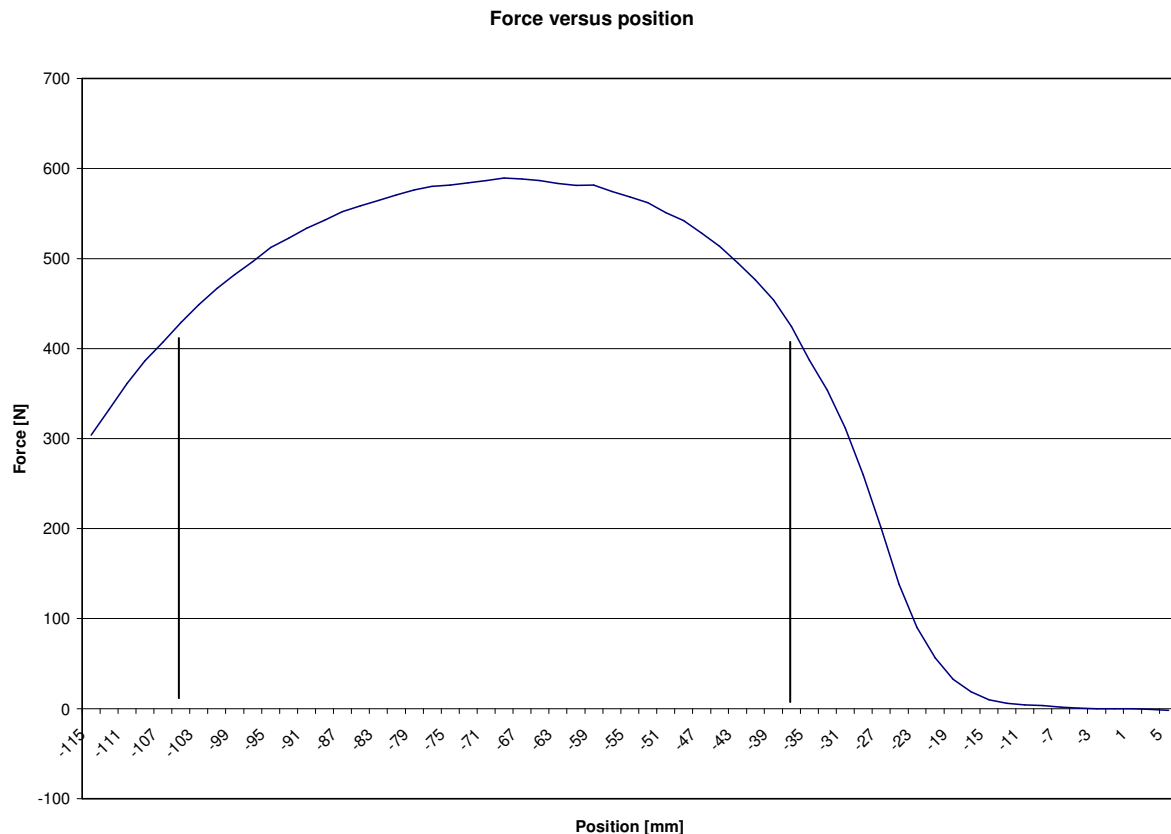


Figure 5.2: Force versus position

For the given positions, the total solenoid characteristic with the position versus force, energy absorbed by the plunger, plunger speed without the ball and ball speed is given in Fig. 5.3.

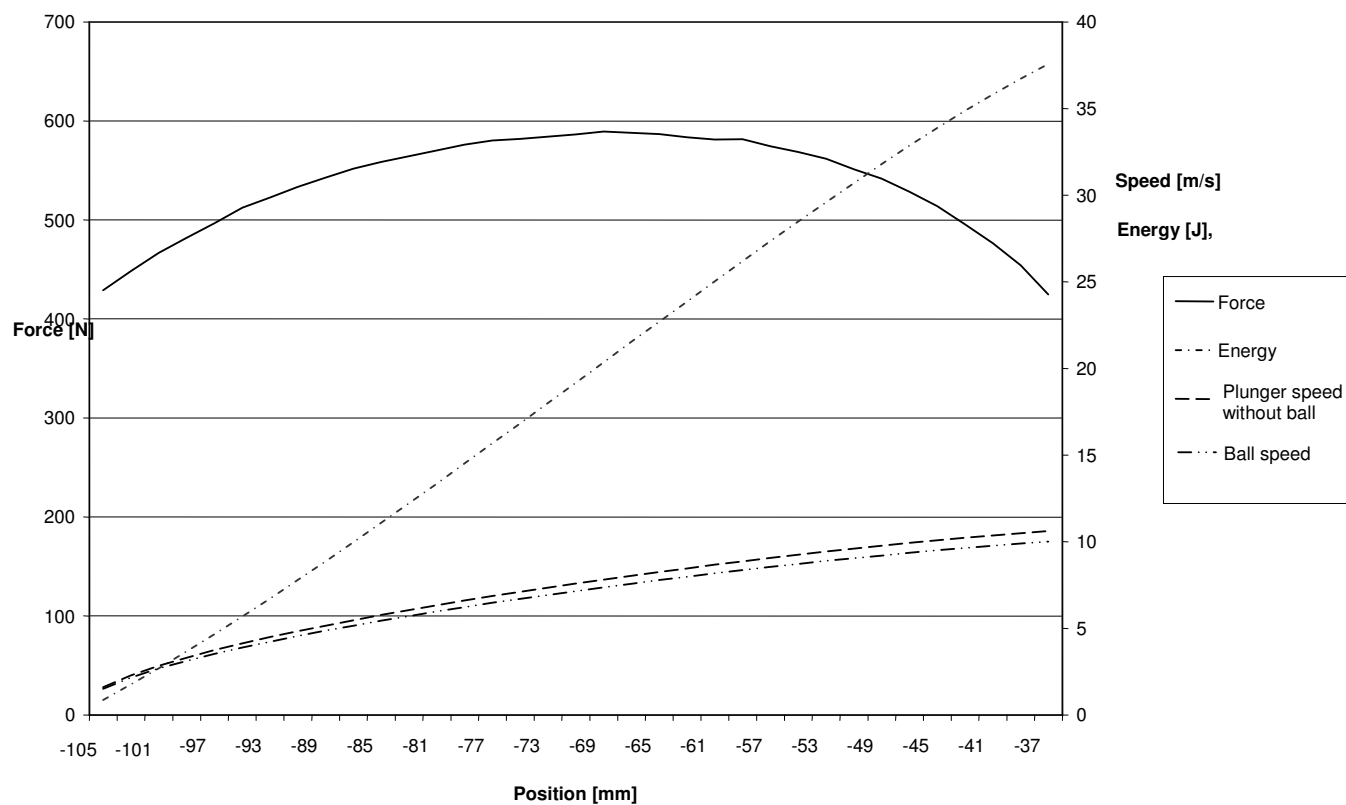


Figure 5.3: Solenoid characteristic

5.3 Shooting parameters

Eq. 4.6 is an indication used for the inductance. This equation holds for coils with no plunger in it. In the solenoid designed, the plunger is already partially present in the coil in the first phase. Therefore, the inductance (L) of the solenoid equals 0.1035 Henries. The resistance (R) is also encountered in FEMM and is 4.18517 Ohms.

With these two parameters and Eq. 4.9, the typical time constant can be calculated. This time constant (τ) is 0.02473 seconds. The reaction time of the solenoid is five times the time constant, which is 0.12365 seconds. The plunger has to be hold at its begin position during this reaction time. After this, the solenoid works at full power and can be released. The plunger can be kept at its position by a mechanical tool added to the solenoid.

The average velocity of the plunger is 7.15 m/s, so the plunger travels in about 10 milliseconds from the begin position till the end position. This together with the reaction time takes about 0.134 seconds to shoot. This time combined with the 20A and 84V the solenoids works with, results in an energy consumption of about 225 J per shot.

5.4 Temperature

The heat production of the coil causes a temperature rise. This rise has to be small, to prevent melting. The equation for the temperature rise due to the heat production is [12]:

$$Q = m_{coil} \cdot c_{copper} \cdot \Delta T \quad (5.1)$$

Here c_{copper} is the specific heat of the material of the coil, $c_{copper} = 387 \text{ J/(kg K)}$. The mass of the coil is easily calculated by multiplying the wire cross-section area times the length by the mass density of copper, which is, $\rho_{copper} = 8960 \text{ kg/m}^3$. For Q the resistance energy loss is taken, to get a broad approximation. This all results in the following equation [12]:

$$I^2 \cdot R \cdot \Delta t = A_{c,wire} \cdot l_{wire} \cdot \rho_{copper} \cdot c_{copper} \cdot \Delta T \quad (5.2)$$

For 16 AWG, the cross-section area $A_{c,wire}$ is given in Appendix 3 at page 31, $\emptyset_{16 \text{ AWG}} = 1.31 \text{ mm}^2$. To calculate l_{wire} Eq. 4.8 is used, which gives: $l_{wire} \approx 600 \text{ m}$.

This all results in a temperature rise of: $\Delta T \approx 0.1 \text{ K}$ per shot.

6. Conclusion

The requirements for the solenoid and the results of the solenoid designed are all put together in table 6.1. As can be seen in the table, all objectives are obtained. The voltage is even reduced by factor 5 instead of factor 3 and the power is reduced by factor 18, instead of 10. The length of the total system is also much smaller than the maximum length allowed.

Table 6.1: Solenoid properties

Specifications	Objective	Results
Ball speed [m/s]	10 m/s	10.02 m/s
Energy [J]	37.5 J	37.6 J
Transported distance [mm]	70 mm	70 mm
Length [mm]	420 mm	287 mm
Diameter [mm]	95 mm	90 mm
Power [W]	3000 W	1680 W
Current [A]	20 A	20 A
Voltage [V]	150 V	84 V

All the other parameters are all presented in the following table.

Table 6.2: Solenoid parameters

Coil: Length [mm]	105 mm
Wire type [AWG]	16 AWG
Turns [-]	2080
Layers [-]	26
Windings per layer [-]	80
Shield: Material [-]	1020 Steel
Shield: Radial thickness [mm]	10 mm
Shield: Axial thickness [mm]	50 mm
Plunger: Length [mm]	160 mm
Plunger: Radius [mm]	13 mm
Plunger Material [-]	1020 Steel
Plunger speed without ball [m/s]	10.6 m/s
Time constant [s]	0.02473 s
Shooting time [s]	0.134 s
Energy consumption per shot [J]	225 J
Temperature rise per shot [K]	0.1 K

Recommendations

There are still a lot of things to investigate before having the optimal solenoid for the robot. Here are some recommendations for future work.

- Multiple coils:

To get more energy delivered to the plunger, it might be useful to use more than one coil. The coils could be set in series, with a controller which turns the coils on and off at the right moments.

An other option is a couple of coils with a plunger in each of it could be set parallel to each other, connected at the front of the plungers. So the energies created by the different solenoids could be taken together as the energy delivered to the shooting leg.

- Eliminate the reaction time:

The reaction time of the coil could be eliminated. To do this, the start up time has to be taken into count. It is necessary that the current taken at the begin positions of the plunger is taken lower than it is at the end in this case. This makes the reaction time shorter.

- Design a controller

One of the most useful properties of a solenoid is it controllability. It is much easier to control than all other shooting mechanisms, as shown in the previous study [1]. The controller to be designed can be equipped with the following useful properties: Adjustable speed, to get nice passes and controlling the ball when receiving it from an other player. These two should be really useful additions to the robots.

- Geometry

When having different geometric properties the solenoid could also be improved. The larger the transported distance allowed, the more energy can be delivered to the plunger.

The same holds for the height requirement, when the outer radius of the solenoid can be larger. The copper wire can be thicker, which decreases the voltage.

- Safety box

Although the power is very much reduced, it still is dangerous to work with. When designing this system, it is recommended to cover all the dangerous components in a safety box, so nobody would get injured.

- Holding mechanism

A holding mechanism has to be designed to keep the plunger at its beginning position when needed.

- Use of the “Super materials”

It could be useful to work with the materials Superalloy, Silicon Core Iron and Carpenter Electrical Iron, as shown in sections 4.2.3 and 4.3.1. These materials are not used in this study because of the difficulty to obtain these materials. However, when an appropriate supplier is found, perhaps a more detailed look at these materials could be useful. This would give harder shots with the same or less power, when shooting as hard as with the 1020 steel. For example: when the solenoid designed in this study is equipped with a superalloy plunger and shield, with the same dimensions, the energy absorbed in a transported distance of 70 mm is 212J. This is five to six times the energy absorbed in the solenoid designed in this study. This is enough for a kicking speed of about 22 m/s, while still using 20 A and 84 V.

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List of symbols

L	Inductance [H]
R	Resistance [Ohms]
E_{ball}	Energy of the ball [J]
m_{ball}	Mass of the ball [kg]
v_{ball}	Velocity of the ball [m/s]
J_{ball}	Moment of inertia of the ball [m ² kg]
ω_{ball}	Rotational speed of the ball [rad/s]
$E_{solenoid}$	Energy of the solenoid [J]
B	Flux density [Tesla]
H	Magnetic field intensity [A/m ²]
W_c	Magnetic field energy [J]
V	Volume [m ³]
F	Force [N]
δ	Perturbation [m]
U	Voltage [V]
I	Current [A]
\mathfrak{R}	Reluctance [AN]
F	Flux [T]
M	Magneto motive force [A]
l	Length [m]
A_c	Cross-section Area [m ²]
μ	Permeability [H/m]
N	Number of turns [-]
a	Radius of the coil [m]
b	Half the length of the coil [m]
x	Position [m]
R_1	Inner radius [m]
R_2	Outer radius [m]
l_{coil}	Length of the coil [m]
R_{coil}	Resistance of the coil [Ohms]
ρ	Resistance per unit length [Ohms/m]
l_{wire}	Wire length [m]
τ	Time constant [s]
Q	Heat [J]
m_{coil}	Mass of the coil [kg]
c_{copper}	Specific heat [J/(kgK)]
ΔT	Temperature rise [K]
ρ_{copper}	Resistance per unit length of copper [Ohms/m]
Δt	Time [s]
$A_{c, wire}$	Cross-section Area of the wire [m ²]
$\emptyset_{16 AWG}$	Cross-section area of 16 AWG wire [mm ²]
n	Number of layers [-]
d_{wire}	Diameter of the copper wire [mm]
w	Windingfactor [-]

Appendix 1: Time constant figure



Figure A1: Time constant example

Appendix 2: Example of a lua script

```
-- Lua-script for analysing a solenoid
outfile = "FEMM_solenoid_results.txt"
handle=openfile(outfile,"a")
write(handle, "\nFEMMresults of testing a solenoid, made by Bram van Goch\n\n")
write(handle, "Coil is 70mm long\n")
write(handle, "    13.5mm inside radius\n")
write(handle, "    35mm outside radius\n")
write(handle, "    2080 turns \n")
write(handle, "Projectile is 160mm long\n")
write(handle, "    no hole inside, solid cylinder\n")
write(handle, "    13mm outerradius\n")
write(handle, "    made of 1020 steel\n")
write(handle, "    starting 105mm away from center\n\n\n")
write(handle, "Meshsize 5\n\n")
write(handle, "The diameter of the copperwire is 1.29mm\n\n")
write(handle, "\n\nposition in mm | force in Newton | Voltage | Amperage \n\n")
closefile(handle)

-- Opening the right model
open("Solenoid.fem")
-- Save it under a different name to keep the original in tact
mi_saveas("temp.fem")

-- Loop for changing the solenoids position and analysing all the positions
for n=0,21,1 do
    mi_seteditmode("group")
    mi_selectgroup(1)
-- Analyse
    mi_analyze()
    mi_loadsolution()
-- Get the force of the solenoid
    mo_groupselectblock(2)
    f=mo_blockintegral(12)
-- Get the properties of the coil
    current_re, current_im, volts_re, volts_im, flux_re, flux_im =
mo_getcircuitproperties("Coil")
-- Put all the data in the outputfile
    handle=openfile(outfile,"a")
    write(handle,-105+5*n, "\t", f, "\t", volts_re, "\t", current_re, "\n")
    closefile(handle)
    mo_close()
-- Translate the plunger for the next analysis
    mi_movetranslate(0,-5)
end
```


Appendix 3: AWG data

<i>AWG to Metric Conversion Chart</i>				
AWG Number	Ø [Inch]	Ø [mm]	Ø [mm²]	Resistance [Ohm/m]
4/0 = 0000	0.460	11.7	107	0.000161
3/0 = 000	0.410	10.4	85.0	0.000203
2/0 = 00	0.365	9.26	67.4	0.000256
1/0 = 0	0.325	8.25	53.5	0.000323
1	0.289	7.35	42.4	0.000407
2	0.258	6.54	33.6	0.000513
3	0.229	5.83	26.7	0.000647
4	0.204	5.19	21.1	0.000815
5	0.182	4.62	16.8	0.00103
6	0.162	4.11	13.3	0.00130
7	0.144	3.66	10.5	0.00163
8	0.128	3.26	8.36	0.00206
9	0.114	2.91	6.63	0.00260
AWG Number	Ø [Inch]	Ø [mm]	Ø [mm²]	Resistance [Ohm/m]
10	0.102	2.59	5.26	0.00328
11	0.0907	2.30	4.17	0.00413
12	0.0808	2.05	3.31	0.00521
13	0.0720	1.83	2.62	0.00657
14	0.0641	1.63	2.08	0.00829
15	0.0571	1.45	1.65	0.0104
16	0.0508	1.29	1.31	0.0132
17	0.0453	1.15	1.04	0.0166
18	0.0403	1.02	0.823	0.0210
19	0.0359	0.912	0.653	0.0264

<i>AWG to Metric Conversion Chart</i>				
AWG Number	Ø [Inch]	Ø [mm]	Ø [mm²]	Resistance [Ohm/m]
20	0.0320	0.812	0.518	0.0333
21	0.0285	0.723	0.410	0.0420
22	0.0253	0.644	0.326	0.0530
23	0.0226	0.573	0.258	0.0668
24	0.0201	0.511	0.205	0.0842
25	0.0179	0.455	0.162	0.106
26	0.0159	0.405	0.129	0.134
27	0.0142	0.361	0.102	0.169
28	0.0126	0.321	0.0810	0.213
29	0.0113	0.286	0.0642	0.268
AWG Number	Ø [Inch]	Ø [mm]	Ø [mm²]	Resistance [Ohm/m]
30	0.0100	0.255	0.0509	0.339
31	0.00893	0.227	0.0404	0.427
32	0.00795	0.202	0.0320	0.538
33	0.00708	0.180	0.0254	0.679
34	0.00631	0.160	0.0201	0.856
35	0.00562	0.143	0.0160	1.08
36	0.00500	0.127	0.0127	1.36
37	0.00445	0.113	0.0100	1.72
38	0.00397	0.101	0.00797	2.16
39	0.00353	0.0897	0.00632	2.73
40	0.00314	0.0799	0.00501	3.44