

Design and realization of a solenoid for a Robocup kicking device

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Traineeship report

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Abstract

In this study, a prototype of a solenoid is designed, built, and tested. The solenoid will be used as kicking device in the turtle robots of the TechUnited Robocup team [5]. Earlier studies have investigated a solenoid as shooting mechanism. In one study the solenoid is investigated as most suitable kicking device [1]. The other study designed and optimized a solenoid [2]. In this study a prototype solenoid is designed and tested.

First, the design is tested in a computer program called FEMM. The main output of the program is the force on the plunger at several positions. Based on this information, the end speed of the plunger and the ball are calculated.

To compare the real solenoid behavior with the simulation, some different tests are done. The first test is a force measuring setup in which the real force is measured at several plunger positions. Out of force the motor constant can be determined. With the motor constant, the final speed of the plunger can be calculated. The second test are some shots at different currents. During this test the current and the traveling time of the plunger are measured. With the plunger movement and traveling time, the final speed can be calculated.

Finally, the calculations from the tests are compared to the output of the simulation. It becomes clear there is a good correspondence between the simulation and experimental results. Based on the outcome of this study, recommendations are given for the actual implementation of the solenoid in the robot.

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1 Introduction

Since 2005 the Technische Universiteit Eindhoven (TU/e) participates in the Robocup competition with the TechUnited team [5]. Robocup [4] is an international project to promote technical research. This is done by setting up a soccer game for robots. In the form of this game, a wide range of technologies must be integrated and examined. Think is this on: intelligent robotics, artificial intelligence, etc. The ultimate goal of the Robocup project is:

By 2050, develop a team of fully autonomous humanoid robots that can win against the human world champion team in soccer [4].

The team of the TU/e participates in the middle size league. In this study, a prototype of a solenoid is designed, built, and tested. The design is based on earlier studies [6, 3]. The solenoid will be used as kicking device in the turtle robots of the TechUnited Robocup team [5]. Furthermore, in the future it will be necessary to shoot at different speeds. The reason for this is a change of the rules. The most important changes are the increase in the number of players (4 to 6) and the extension of the field (twice as large). For this reason, team play gets a very big role. To make this possible, the ball handling and shooting mechanism, with adjustable shooting velocity, become a very important aspect of the game.

The task for this project is to design a solenoid shooting mechanism which makes team play possible. The shooting mechanism should be able to switch between different shooting speeds. Different shooting speeds are necessary to shoot at the goal (fast), pass the ball to another robot (speed depending on the distance), or shoot over another (opponent) robot. This all has to fit in the robot and must work properly with the power available.

2 The basic physics

2.1 The solenoid principle

The principle of a solenoid is based on a electric generated magnetic field. When sending a current trough a coil, a very strong magnetic field can be created. This field is then used to accelerate a plunger or projectile through the coil. The plunger or projectile gets a kinetic energie when a current is set on de coil. This is used to shoot the ball. In Fig. 1 a solenoid is schematically represented.

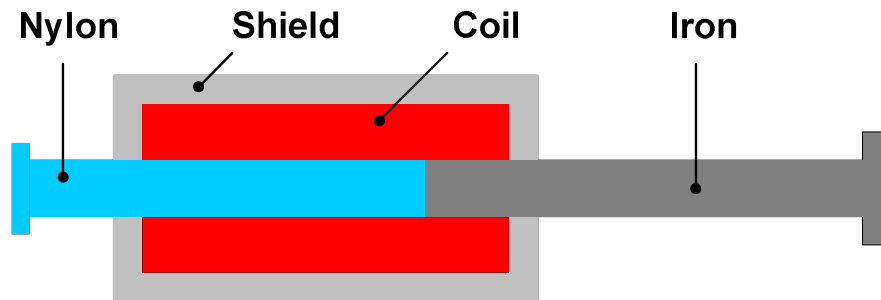


Figure 1: Solenoid

To understand the working of a solenoid, the basic physics of electric generated magnetic fields will be discussed in the remainder of this chapter.

2.2 Magnetic Field and Flux

First the basic physics of a solenoid will be treated. The basic physics involve electric generated magnetic fields and fluxes. This section gives a ruff overview [1].

The magnetic force on a moving charged particle can be calculated as:

$$\mathbf{F} = q\mathbf{v} \times \mathbf{B} , \quad (1)$$

where \mathbf{F} is the magnetic force, q the charge, \mathbf{v} the velocity and \mathbf{B} the magnetic field or magnetic flux density. The unit of \mathbf{B} is called *tesla*. The gauss G ($1 \text{ G} = 10^{-4} \text{ T}$) is also commonly used.

$$1 \text{ tesla} = 1 \text{ T} . \quad (2)$$

The graphical representation of (1) is given in Fig 2. The magnetic field lines are represented by \mathbf{B} . On the left side of the figure, the velocity \mathbf{v} is parallel or antiparallel to the magnetic field \mathbf{B} . So the magnetic force is zero. On the right side the velocity is perpendicular to \mathbf{B} . Now the magnitude of the magnetic force $F = qvB$

If lines are draw so that the line through any point is tangent tot the magnetic field vector \mathbf{B} , the magnetic field is represented by magnetic field lines. Because the direction

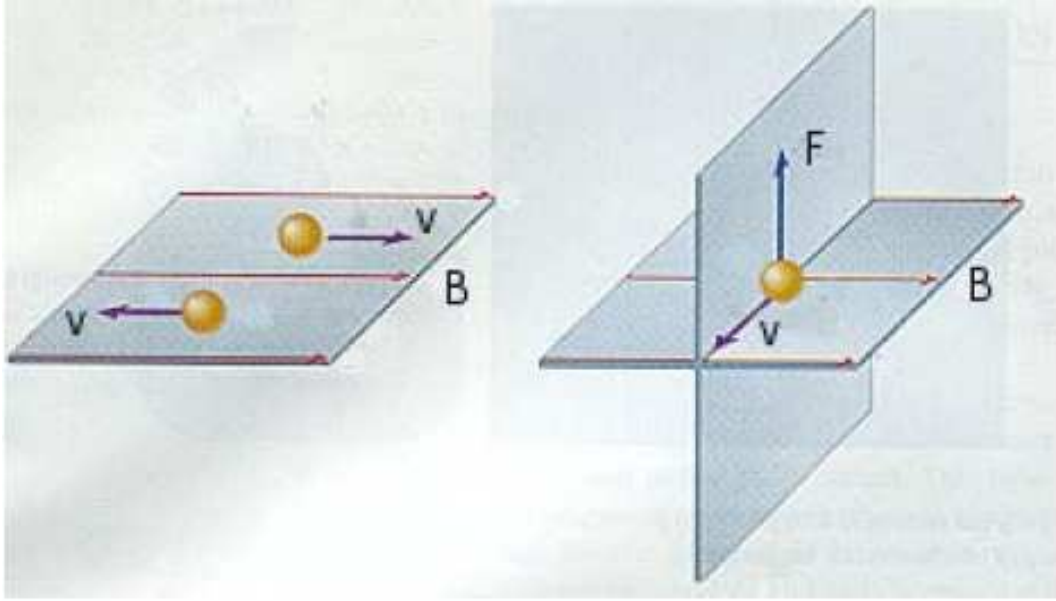


Figure 2

of \mathbf{B} is unique at each point, the field lines never intersect. Some magnetic field lines are shown in Fig. 3. Only a few representative lines are drawn. At locations where the lines are close together, the field strength is large (and vise versa).

Now the magnetic field \mathbf{B} is known, the magnetic flux Φ_B through any surface can be calculated. This can be done by dividing the surface into small elements dA and determining the component of \mathbf{B} normal to the surface, B_{\perp} . In general, the component varies from point to point on the surface. The change in magnetic flux $d\Phi_B$ through this area is defined as

$$d\Phi_B = B_{\perp} dA = \mathbf{B} \cdot d\mathbf{A} . \quad (3)$$

The total magnetic flux through the surface is the integral of the contributions over all the individual area elements. This is also known as Gauss's Law [1]

$$\Phi_B = \int B_{\perp} dA = \int \mathbf{B} \cdot d\mathbf{A} . \quad (4)$$

The unit of the magnetic flux is equal to the unit of the magnetic flux density, tesla (T), times the unit of area (m^2), and is called the weber (Wb).

$$1 \text{ Wb} = 1 \text{ T } m^2 . \quad (5)$$

The next thing to look at is how to create a magnetic field with a electric charge. As shown before, a magnetic field only exerts a force on a moving charge. Conversely only a moving charge creates a magnetic field. The magnetic field \mathbf{B} is proportional to the amplitude $|q|$ of the applied charge. The magnetic field \mathbf{B} is also perpendicular to the plane

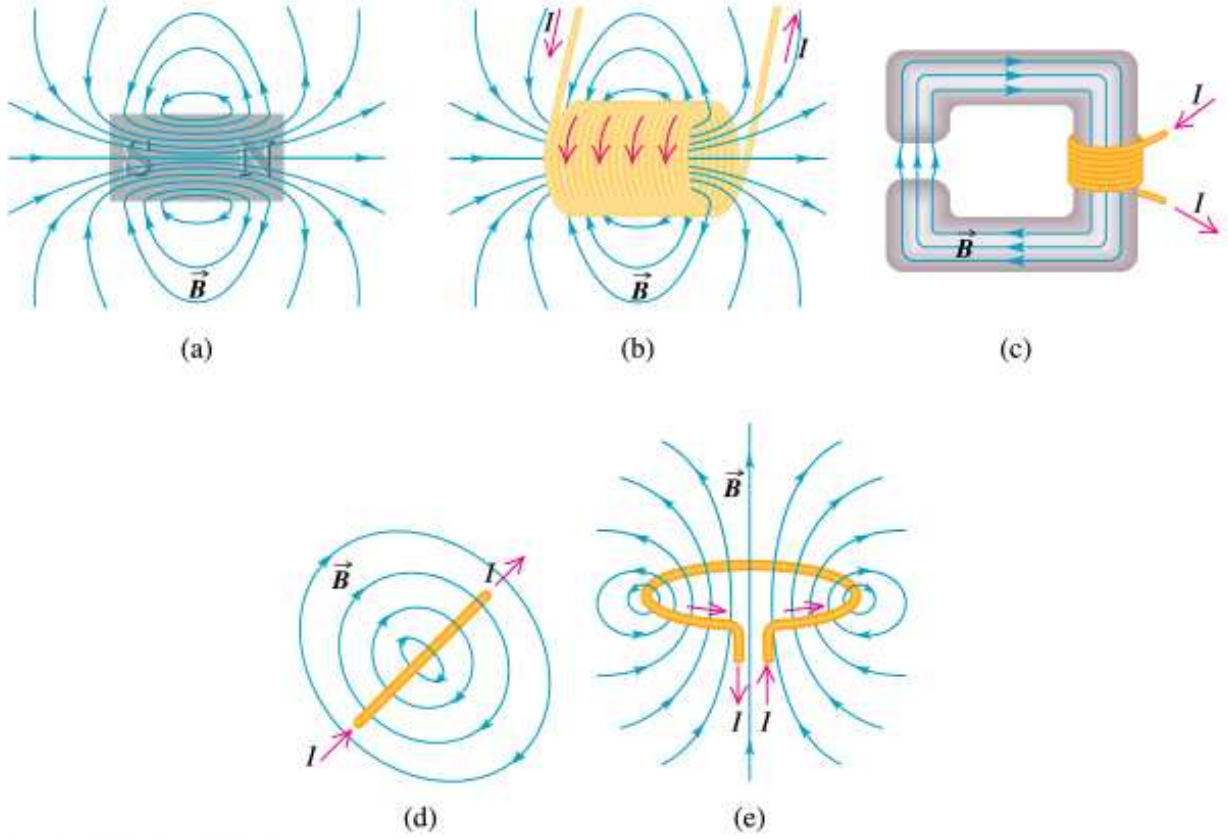


Figure 3: magnetic field lines

containing the line from the sources point (q) to the field point (P) and the velocity vector \mathbf{v} of the particle. The magnitude of \mathbf{B} is proportional to the particle's speed v shown in Fig. 4.

The magnetic field in point P (of Fig 4) can now derived with (6). This formula holds for a charge with constant velocity [1].

$$\mathbf{B}_p = \frac{\mu_0}{4\pi} \frac{q\mathbf{v} \times \hat{\mathbf{r}}}{r^2} \quad (6)$$

The therm $\mu_0/4\pi$ is a proportional constant and $\hat{\mathbf{r}}$ is the unit vector (defined as the vector \mathbf{r} from the source to the field point divided by its magnitude $\hat{\mathbf{r}} = \mathbf{r}/r$).

The magnetic field of a current element can now be derived. This is almost equal to the total magnetic flux through a surface of (4). The first step is to calculate the magnetic field produced by a short segment $d\mathbf{l}$, see Fig. 5.

When the length and area of the segment are known, the moving charge dQ of the segment can be calculated as

$$dQ = n q A dl , \quad (7)$$

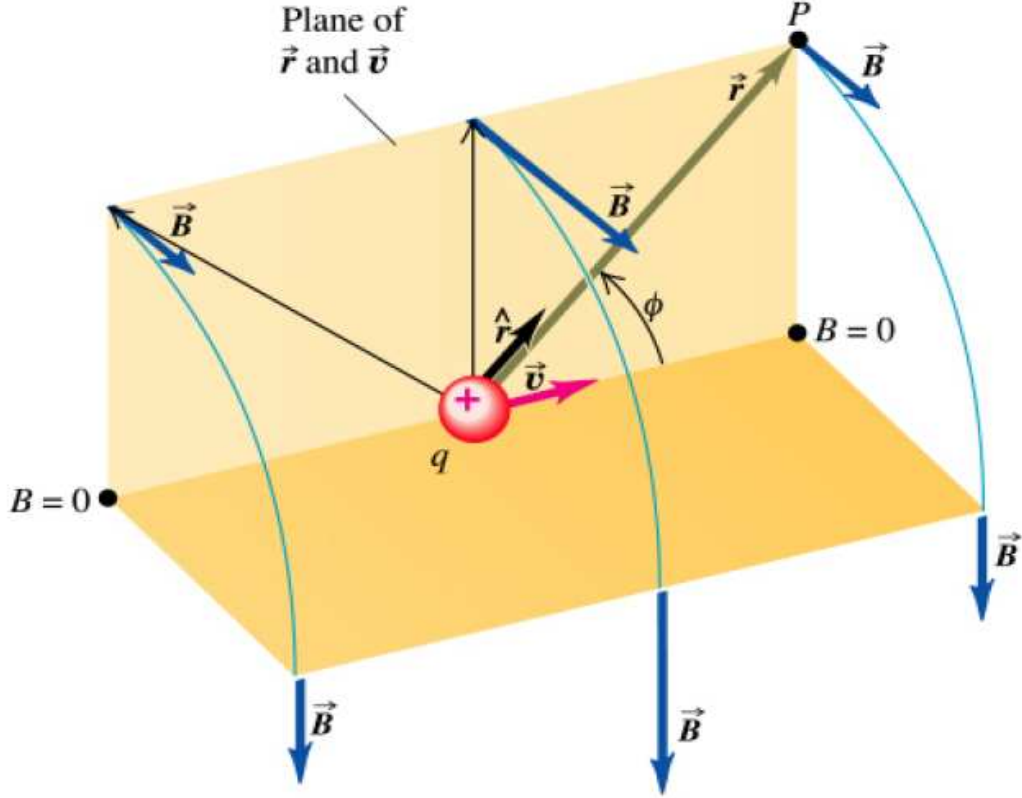


Figure 4: The magnetic field vectors from a moving charge q

where n are the number of moving charged particles with charge q . Substitution (6) in (7) gives

$$dB = \frac{\mu_0}{4\pi} \frac{|dQ|v_d \sin \phi}{r^2} = \frac{\mu_0}{4\pi} \frac{n|q|v_d A dl \sin \phi}{r^2}, \quad (8)$$

in this formula v_d is the drift velocity through the segment. The current $I = n|q|v_d A$. When using vector $\hat{\mathbf{r}}$, the equation can be written in vector notation, which is also known as the law of Biot and Savart [1]

$$d\mathbf{B} = \frac{\mu_0}{4\pi} \frac{I d\mathbf{l} \times \hat{\mathbf{r}}}{r^2}. \quad (9)$$

The total magnetic field caused by moving charges is now equal to the vector sum of the fields caused by the individual charges. This can be done by investigating (9) over all segments $d\mathbf{l}$. The general equation for deriving the magnetic field \mathbf{B} caused by a electric current I becomes

$$\mathbf{B} = \frac{\mu_0}{4\pi} \int \frac{I d\mathbf{l} \times \hat{\mathbf{r}}}{r^2}. \quad (10)$$

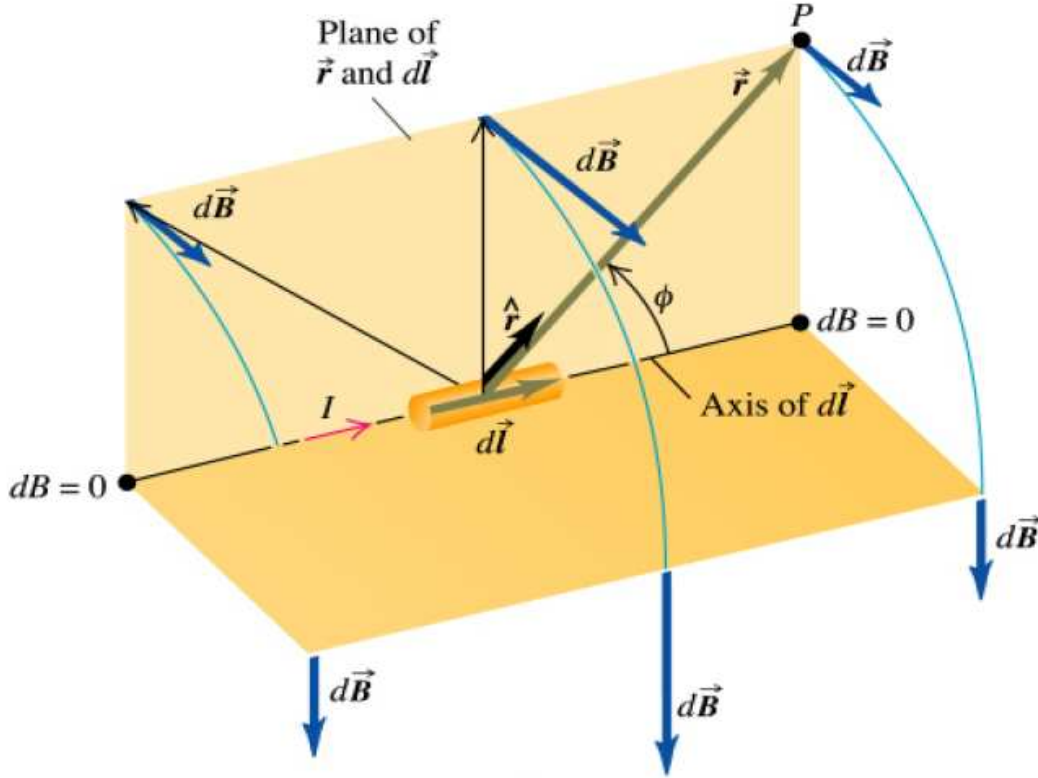


Figure 5: The magnetic field vectors from a current element $d\vec{l}$

In Fig. 7 the magnetic field in a circular current loop is shown. This is mostly the same as the two parallel conductors of Fig. 6, however in a circular way. The field lines for the circular current loop are closed curves that encircle the conductor. This is the basic idea of a solenoid. Only a solenoid has many circular current loops. This is also schematically shown in Fig. 7, only a few turns are shown.

2.3 Time constant

When a current is present in the coil, a magnetic flux through the coil is built up. This flux changes when the current changes. So, a coil that carries a varying current has an electromotive force (emf) induced on it by the variation in its own magnetic field. This self-inductance is simply called inductance. The self-induced emf ε in a coil (from Faraday's law [1]) is given as

$$\varepsilon = -L \frac{dI}{dt} . \quad (11)$$

The SI unit for inductance is Henry ($1 \text{ H} = 1 \Omega \text{ s}$). Lenz's law says that the self-induced emf in a circuit opposes any change in the current in that circuit. Because of this the minus

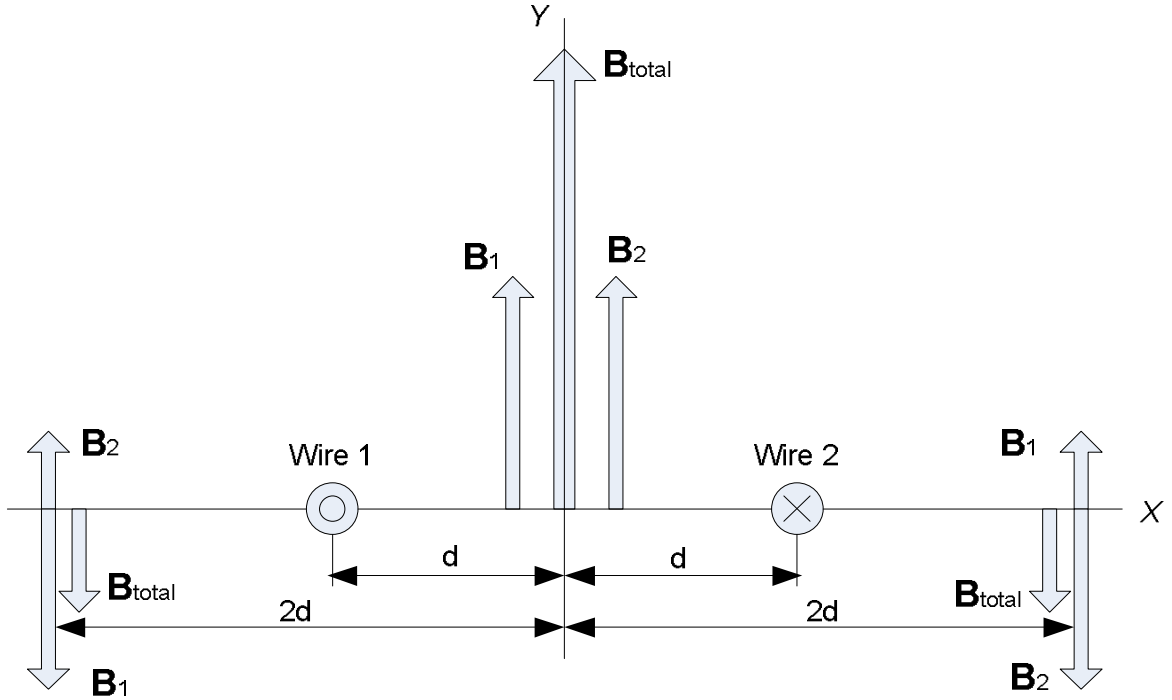


Figure 6: The magnetic field vectors from a two parallel conductors

sign is added [1]. A circuit designed to have a inductance (such as a coil) is simply called an inductor.

This all means that it is difficult to rapidly change a current through a circuit which include a inductor. The inductor in this case is the coil of the solenoid. The coil is normally modeled as a R-L circuit (a circuit that includes a resistor (R) and an inductor(L)). The growth, in time, of the current is first order

$$I = \frac{\varepsilon}{R} (1 - e^{-(R/L)t}) . \quad (12)$$

At a time equal to L/R , the current has risen to $(1 - 1/e)$. The quantity L/R is a measure of how quickly the current builds up towards its final value. This is called the time constant. The time constant for an R-L circuit, denoted by τ , is

$$\tau = \frac{L}{R} . \quad (13)$$

In a time equal to τ , the current reaches 63% of its final value; in 2τ , 86% and in 5τ , 99.3%. The growth (and decay) of the current is shown in Fig. 8 [3].

For the working principle of the solenoid, this means that the plunger must be held on its initial position. When the current is at a certain level (say 96%), the plunger must be released. Then the solenoid works at maximum efficiency and power.

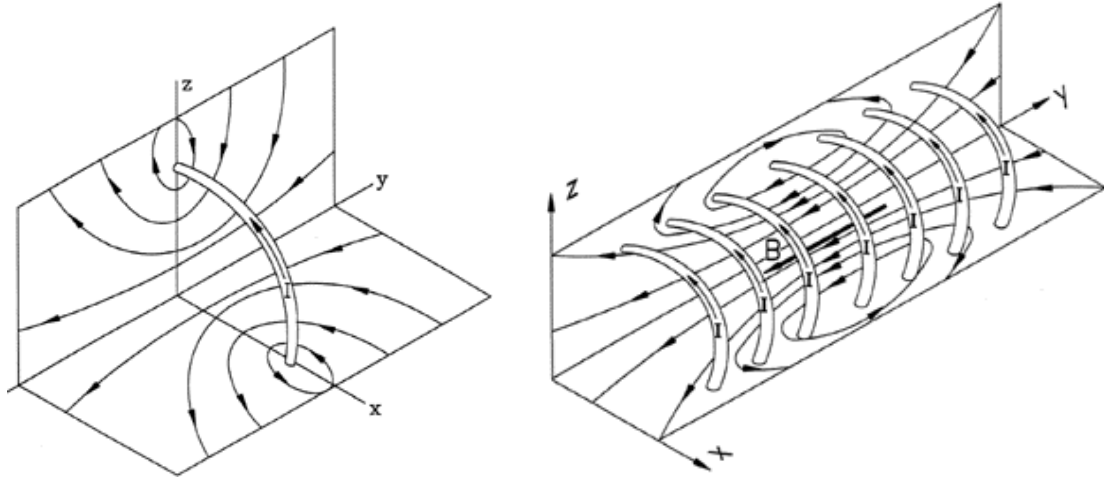


Figure 7: The magnetic field of a circular current loop [left] and a solenoid [right]

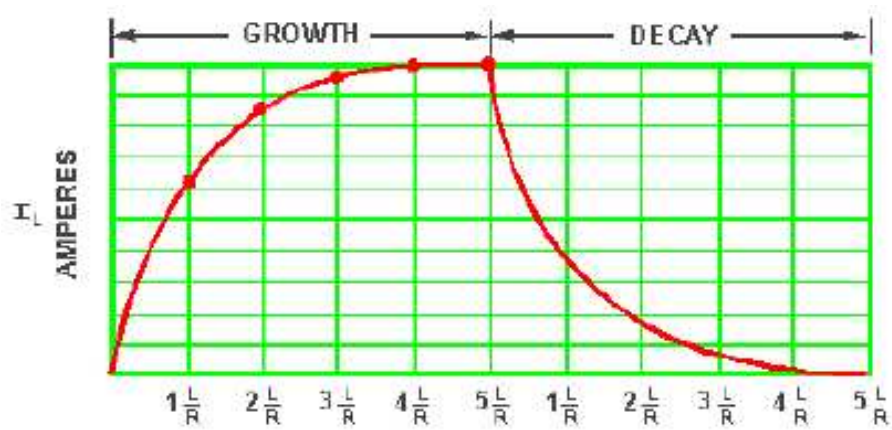


Figure 8: Time constant of the solenoid coil

3 Designing a solenoid

The prototype solenoid will be based on the solenoid optimization as described in [3]. The design is based on optimizing a Finite Element Method Magnetics (FEMM) model. FEMM is program to calculate 2-dimensional and axis-symmetric time independent magnetic problems. The program uses Maxwell equations in combination with the finite element method [2]. How the FEMM program performs the calculations, is described in the subsection below. The the originally designed solenoid [3] is based on the optimizing of these calculations.

3.1 Calculations with FEMM

First the prototype of the solenoid is drawn in the program. When al the components are drawn, the material properties are attached to the components. The FEMM material library contains all the material properties (for the B and H values) to calculate the magnetic field co-energy W_c . Now FEMM can calculate the magnetic field using (14). In this formula, H' represents the nonlinear field intensity.

$$W_c = \int \left(\int_0^H B(H') dH' \right) dV \quad (14)$$

To compute the force from the co-energy, the currents, trough the coil, is held constant. The position of the object upon which the force acts is perturbed slightly. The force can then be estimated by

$$F = \frac{W_c(x + \delta) - W_c(x)}{\delta}, \quad (15)$$

where x denotes the initial position and $x + \delta$ denotes the perturbed position. The calculated force F acts along the direction of the perturbation. When the force F is calculated for all points the total energy of the solenoid can be calculated as

$$E_{solenoid} = \sum_{i=1,2,\dots}^n F(x_i) \delta_i. \quad (16)$$

This is the energy which is stored in the plunger. When the mass of the plunger is known, the speed is easy to calculate with

$$E_{solenoid} = \frac{1}{2} m_{plunger} v^2. \quad (17)$$

The momentum of the plunger can then be calculated by

$$p = m v. \quad (18)$$

When the momentum of the plunger is known the impulse (to the ball in the end) can calculated as

$$J = \sum F \Delta t = \frac{p_2 - p_1}{t_2 - t_1} \Delta t. \quad (19)$$

3.2 The optimized solenoid

In [3], the components of the solenoid are optimized. The main components are the coil, the plunger and the shield. The solenoid is visualized in Fig. 9. The parameters of the components are given in table 1.

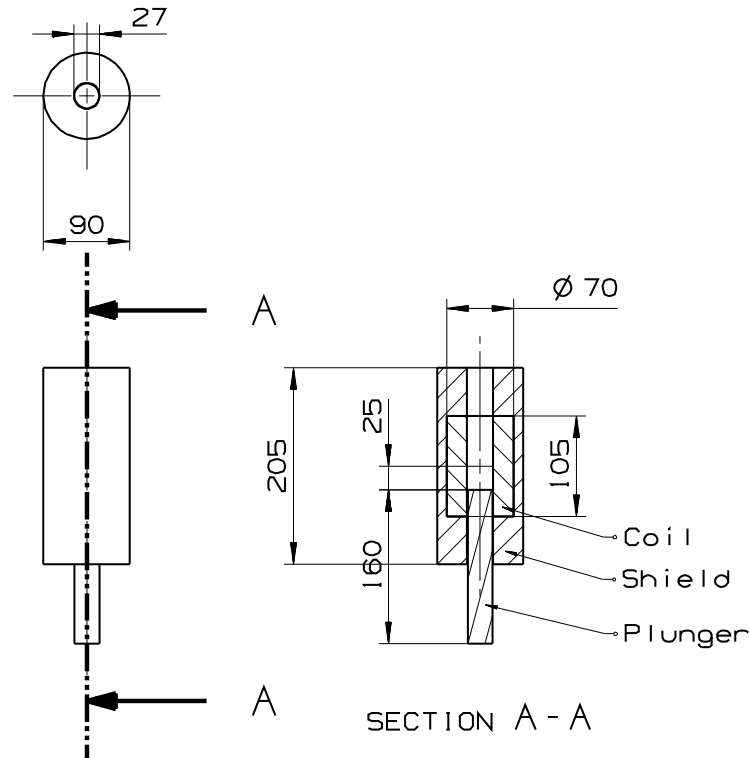


Figure 9: Original Design

Out of these parameters a sufficient prototype will be designed. This will be discussed in the remainder of this chapter.

3.3 Design of the prototype

To design a sufficient prototype, one important thing has to be taken into account. The robots are powered with 3 Makita batteries. These are Ni-MH batteries with 24 V and 3.3 Ah. The shooting mechanism may only use one of these batteries. This means that there is only 24 V from one battery available for the solenoid. This is not a big problem because a capacitor can be used. With the Makita batteries, the capacitor can be charged. Furthermore there are only European wire diameters available at the TU/e. So the 16 AWG is not an option for the prototype. So only the wire has to be changed (this also changes the turns and layers). The requirement of 16 AWG can be approached with a wire of 1.25 mm,

Coil		Plunger	
Lengt	105 [mm]	Lengt	160 [mm]
Wire	16 [AWG]	Diameter	26 [mm]
Turns	2080 [-]	Material	1020 Steel
Layers	26 [-]	Movement	70 [mm]
Shield		Solenoid	
Radial thickness	10 [mm]	Speed	10.6 [m/s]
Axial thickness	50 [mm]	Current	20 [A]
Material	1020 Steel	Voltage	84 [V]

Table 1: parameters from [3]

1165 turns and 35 A. The results are shown in the Fig. 10. The end speed of the ball is about 7.4 m/s.

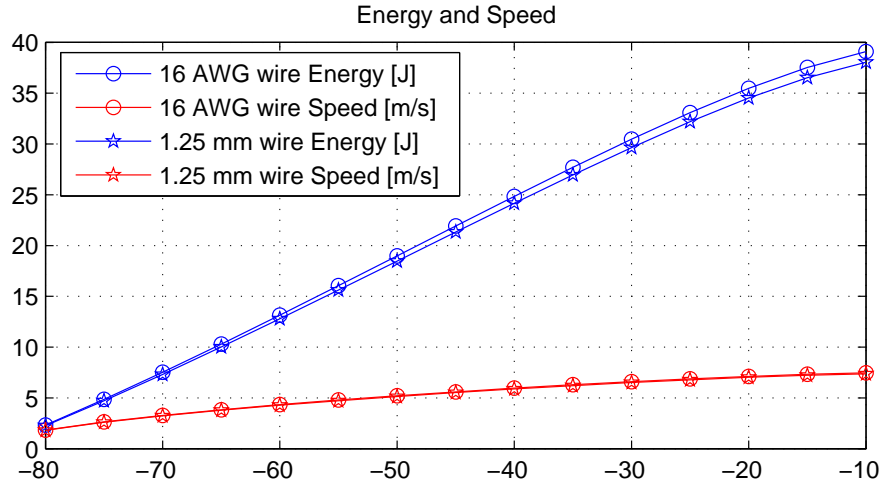


Figure 10: Results of the 16 AWG and 1.25 mm wire

Also the other components have to be changed. The shield has to be split in to parts, otherwise the coil can never be placed inside. The shield is made square instead of circular. The reason for this is that the solenoid prototype can be easier handled for testing. The shield has also a bearing to move the plunger in and out with low friction. The plunger has an aluminium end. Because of this, some turbulent flow arise in the magnetic field. This end aluminium end punches the ball and can be used to place some sensors at during testing. At the end of the plunger, a bulge is made. This is to stop the plunger at the end position. Between the shield and the bulge a rubber ring are placed to soften the impacts. The movement is only 65 mm instead of the 70 mm as shown in Table 1. The other reason is from securities considerations, it prevents the plunger to move out of the solenoid. The

final prototype design is shown in Fig. 11. The drawings of the components are included in Appendix A.

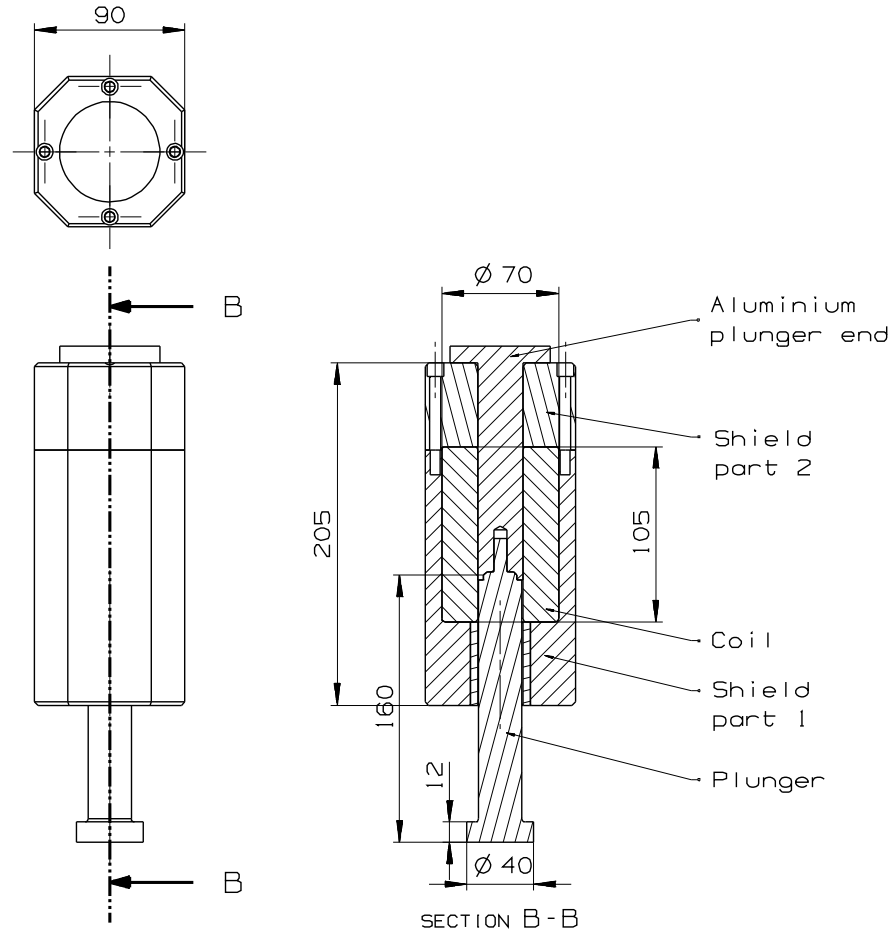


Figure 11: Prototype Design

4 Test setup

When the solenoid prototype is built it has to be tested. To test the solenoid, an electric circuit is developed. The circuit is designed such that the electric parameters can varied easily. The first thing which is needed is a power source. The source can vary from 0 to 300 V. The source charges a capacitor whit a capacity of 4.7 mF. Between the capacitor and the source, a resistor is placed. When the capacitor is full, the switch can be closed and the full energy of the capacitor is released over the coil of the solenoid. The coil has an inductance of 15.8 mH and a resistance of 2.5 Ω . An extra diode is placed over the coil. In this way, the coil can unload its energie when the switch is open. The electrical circuit is shown in Fig. 12.

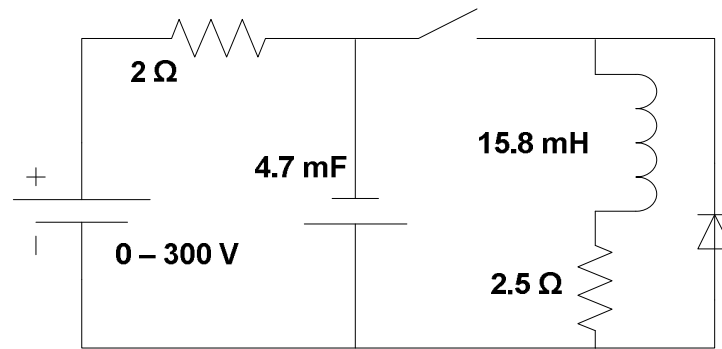


Figure 12: electric circuit

To compare the test with the simulation the motor constant has to be determent. This is done by measuring the force with a special load cell. The motor constant is different at every position of the plunger. To get a good indication, several plates of 8 mm are placed. In this way the motor constant can be determent at intervals of 8 mm. The test setup for this experiment is shown in Fig. 13.

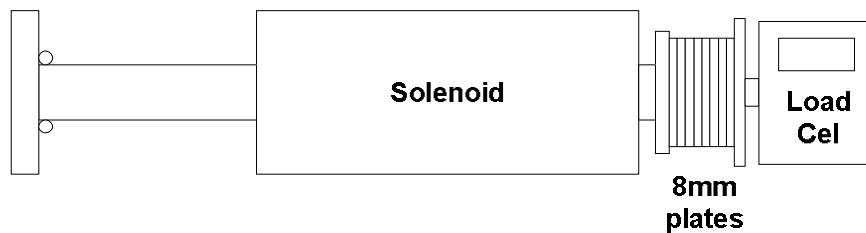


Figure 13: force measuring setup

5 Results

5.1 Simulation results

Now the design of the prototype is ready, all the final dimensions are known. To get a good simulation outcome, the final prototype is modeled in FEMM and all the calculations are made. The most important thing which does not match the theory is the coil. The wire is not exactly 1.25 mm in diameter. Another important difference is the weight of the plunger. This is 1.0 kg instead of 0.6 kg. Also for the test the current is set at approximately 45 A. When running the simulation again for the prototype, the energy and speed are recalculated. The result is shown in Fig. 14. The end speed of the plunger is about 8.2 m/s at 5 mm (because a rubber ring of 5 mm is added). The distance is the distance that the plunger moves before it hits the shield.

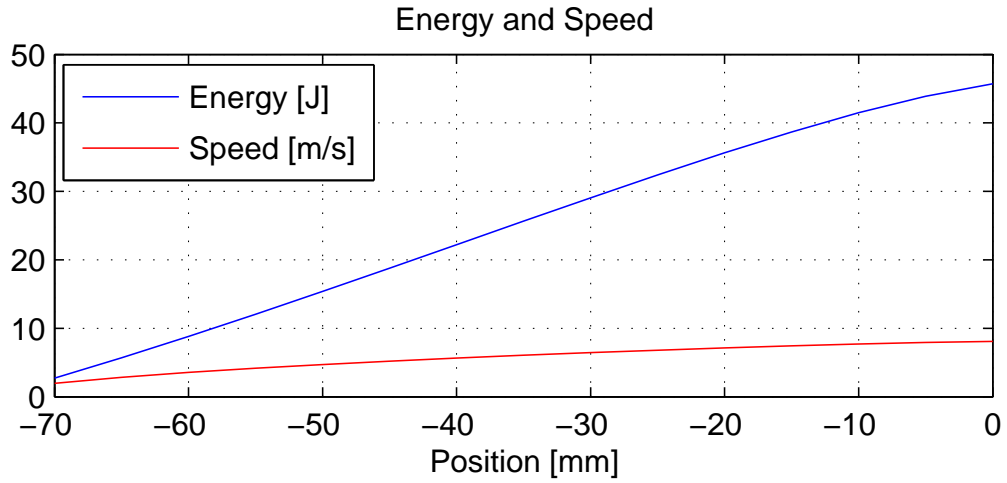


Figure 14: Calculated energy and speed for the prototype

The above simulation is at the full current. As described before, an inductor has a time constant. So the plunger must be held on its initial position until the current is at its maximum. The time constant equals

$$\tau = \frac{L}{R} = 0.0150 . \quad (20)$$

When plotted (see Fig.15), it is easy to see that the plunger must be released after 0.06 seconds. After this time, the current is at 98% of its maximum and the solenoid works at almost full power.

5.2 Test results

The simulation program FEMM gives a force as output. So the most important measurement is the force measurement. With this measurement the simulation can easily be

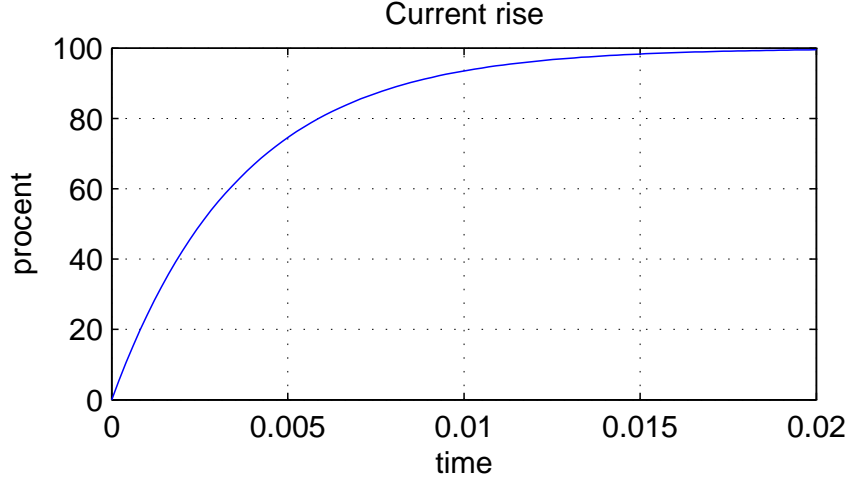


Figure 15: current rise in the L-R circuit

compered with the real solenoid. The force is measured as descried in section 4 (test setup). The force is measured each 8 mm (see fig13). The results of the test and the simulation are given in table 2. This force measuring test is done with a current of 9 A. This is because the test take some time and when a high current is set, the coil becomes very hot.

Position [mm]	Motor constant [N/A]	Measured force [N]	Simulated force [N]
77	5.53	44.20	44.19
69	8.00	64.00	63.69
61	10.17	81.32	81.18
53	11.30	90.40	90.84
45	11.93	95.40	95.14
37	12.06	96.45	96.16
29	12.23	97.80	94.32
21	12.48	99.80	88.51
15	12.94	103.50	80.52

Table 2: parameters

To calculate the acceleration and velocity at the desired 45 A, the above measured motor constant (measured with 9 A) is important. Calculating the acceleration from the motor constant (k_p), first the force must be calculated. The average force over the full length (at 45 A) became

$$F_{average} = k_p I = 483.2 \text{ N} \quad (21)$$

Now the force is known the acceleration became

$$a = \frac{F_{average}}{m} = 439.3 \text{ m/s}^2 . \quad (22)$$

Calculating the velocity from the acceleration gives

$$v = a t = 7.9 \text{ m/s} . \quad (23)$$

With some basic formula's the speed can also calculated from the test (Fig. 16) with the desired 45 A. The test is a free shot with the solenoid. During the shot a scope measures the current. The measuring begins when the acceleration starts. After 18 ms there are some peaks in the acceleration (Fig. 16). Here the plunger hits the shield. The distance is 65 mm and the time needed to travel this distance is 18 ms. So the acceleration became

$$a = \frac{2 s}{t^2} = 401.2 \text{ m/s}^2 . \quad (24)$$

Calculating the velocity from the acceleration

$$v = a t = 7.2 \text{ m/s} . \quad (25)$$

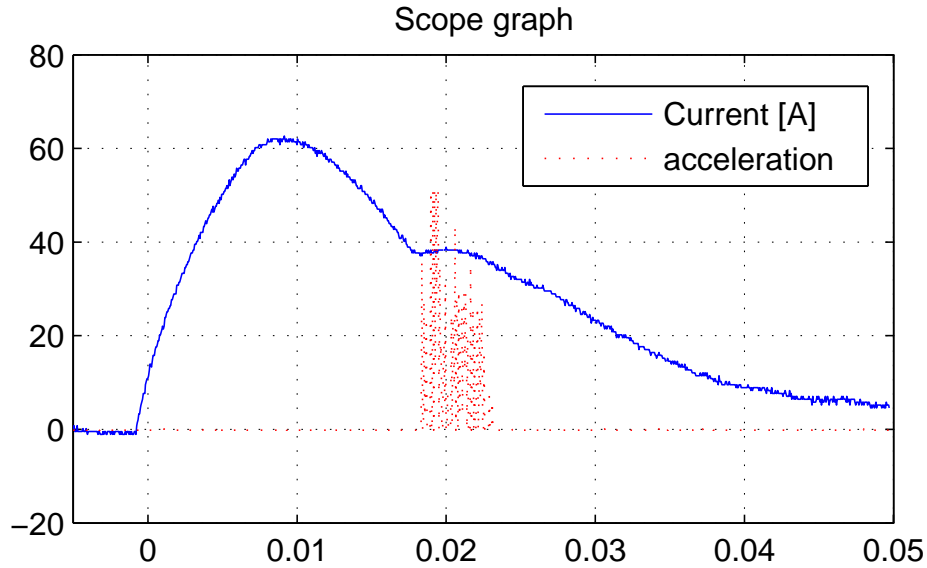


Figure 16: scope graph of the test

6 Conclusions and recommendations

6.1 Conclusions

The solenoid shoot the ball with a sufficient 8 m/s. It is also possible to shoot with different speeds. This can be done by varying the power through the coil with some simple electronics. The switch can be replace by a transistor which is controlled by a pulse source. The speed of the ball is now linked to the time the transistor is open. The time the transistor is open, is controlled by the pulse source.

The tests with the prototype solenoid approximates the simulation good. In table 3 the end speeds of the ball are shown.

Test	Free Shot	Motor constant	Simulation
Speed	7.2 [m/s]	7.9 [m/s]	8.2 [m/s]

Table 3: Results

When comparing the test, in which the motor constant is determent, with the simulation there is a very good similarity. The difference in end speed is only 0.3 m/s. One of the reasons is possibly the material of the plunger. The material of the plunger can not handle a high magnetic field (only 1 Tesla). When the field is much higher the plunger became saturated. This material saturation looks responsible for this little incorrectness.

Comparing the test with the free shot with te simulation the difference is 1.0 m/s. The difference between the test in which the motor constant is determent and test with the free shot, is only 0.7 m/s. Friction, because of the movement of the plunger is probably the main reason for this. The simulation as well as the test in which the motor constant is determent are static. For this reason friction is not taken into account during simulation and the test in which te motor constant is determent.

6.2 Recommendations

The prototype turns out to be a very powerful and silent shooting mechanism. To turn this prototype solenoid into a solenoid shooting mechanisme for the turtle robots, some work has te be done. The most important recommendations to work on are:

- The solenoid has to be designed to fit in the robot. During the prototype tests, the space available for the solenoid is changed.
- The prototype weights around the 10 kg. This is too much for use in the robot. The robots weight is restricted to 40.0 kg. The final solenoid, for the turtle robots, must undergo a weight study to maximize power vs weight.

- Power modulation is needed for shooting at different speeds. To realize this an electronic circuit must be designed. This circuit finally must be controlled by software.
- Take a closer look at turbulent flow in the magnetic field and saturation of the materials. This will give a better resemblance with the simulation. Also try to take the friction into account.

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Appendix A Prototype drawings

