TARGET-B

Localized Cancer Treatment Using Magnetic Particles and Electromagnets

Project Members

Raphael Haehnel	341142107	raphael.haehnel@mail.huji.ac.il
David Telepnev	209460377	david.telepnev@mail.huji.ac.il

Supervisors and Collaborators

Prof. Nadav Katz, The Hebrew University of Jerusalem
Prof. Yoav Mintz, Center for Innovative Surgery, Hadassah Medical Center

Table of contents

I. Abstract


View of the Ein-Kerem campus

One of the main methods to cure cancer is chemotherapy. Although it is a very simple medical procedure, it harms the healthy cells as well: It is a non-localized and destructive treatment. The solution of the Prof. Yoav Mintz from Hadassa Ein-Kerem, and Shlomo Margel, from Bar-Ilan university [1], is, from one part, add paramagnetic particles to the drug, and only then the drug is injected into the body, near the tumor. In a second part, we put magnets next to the body, near the tumor, to pull these particles, and in this way, we prevent the dispersion of the particles across the body.

Our idea, and the objective of the project is to treat the patient's tumor with localized and non-destructive treatment. For that purpose, we had to deal with electromagnets instead of simple magnets. How does it work ? The drug is associated with paramagnetic particles and injected into the patient near the tumor. Then the drug is localized in a bounded area via electromagnets. The fact is that physically speaking, we cannot concentrate magnetic particles in one point (we cannot have a stable equilibrium point). We can bound it, though. We are building a belt of electromagnets that creates a switching magnetic field. The drug executes an oscillating motion around the tumor in response to this field, which prevents it from dispersing. By this way, the particles must be attracted by the electromagnets with a specific frequency and a specific force for each one of them.

We had a few challenges, that were to localize magnetic particles by using magnets and to generate a strong magnetic field. Our solution involves the construction of powerful electromagnets controlled by Arduino and associated with a computer program.

II. Introduction

Electromagnets are widely used as components of many electrical devices, such as motor, generators, relays, doors, MRI, and so on. They could be used in DC mode (like in MRI) as well as in AC mode (like in transformers). Generally, in DC mode, your purpose is to generate a magnetic field, in contrast to AC mode, where the principle idea is to transfer power. For this project, we will be interested to use DC magnetic field.

You might think that to obtain an electromagnet, we simply need to wind some wire around a metallic structure, connect it to a power source, "et voilà" !

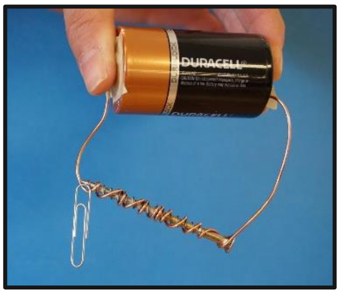


Image from greatbasinobservatory.org

In fact, generate strong and reliable magnetic field is not as simple. To know exactly how much power to inject into each electromagnet, one must begin with the magnetism theory. Only then we could be able to design practical electromagnet, but also to build the electronic circuit than will control it.

From Biot-Savart law we know:

$$B = \frac{\mu_0 I}{2\pi} \int \frac{ds \times r}{|r|^3}$$

This can be resolved to obtain the field from a circular coil carrying current. The total magnetic field at a point which is at a distance z from the axis of a circular coil of radius R is:

$$B(0,0,z) = \frac{\mu_0 I n R^2}{2 \cdot (R^2 + z^2)^{\frac{3}{2}}}$$

Where μ_0 is the permeability of free space ($\mu_0 = 4\pi \cdot 10^{-7}$), I is the carrying current and n is the number of loops.
So, for our system of two coils without magnetic core we get:

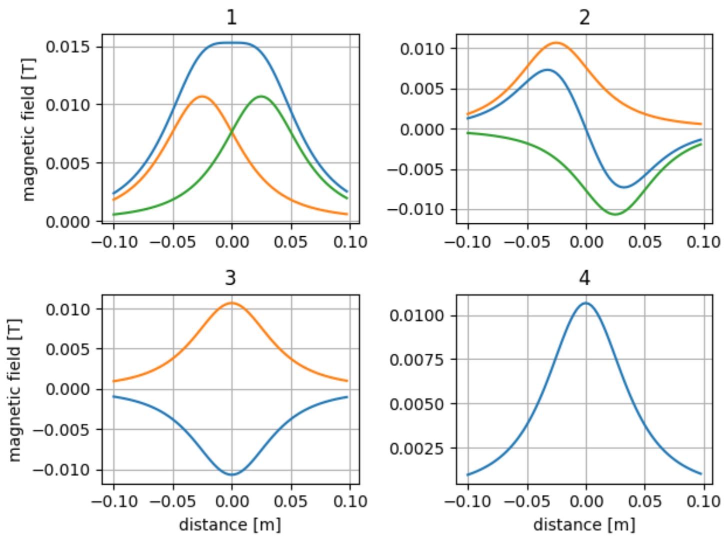


Figure 1 - Two coils in superposition give Helmholtz configuration (1), anti-Helmholtz configuration (2), two coils with different current direction at the same point in space (3), one coil (4)

In figure 2 we can see the magnetic lines created from the coil part in the electromagnets that we build. By using a magnetic core, we get an increase in the magnetic field strength via the concentration of the magnetic field (more dense lines on the vertical axis outside the electromagnet) and the magnetic field created of the core itself. This happens as result of using ferromagnetic material as the magnetic core.

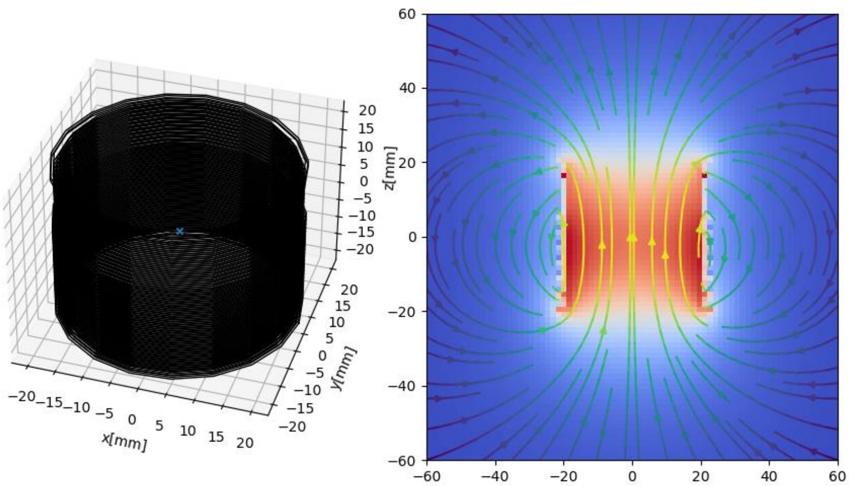


Figure 2 - 180 windings coil, and magnetic field strength with direction

Ferromagnetic material is made of “domains”, the dipoles in each domain are aligned in the same direction. In normal situation there are a lot of such domains that each domain points in different direction (randomly) and because of this they cancel each other. So, the net magnetic field is equal to zero.

Applied to an external magnetic field, the domains of the ferromagnetic material start to align in the same direction until we get to saturation. This process is called hysteresis. In such a way this material can be characterized by a possible permanent magnetization.

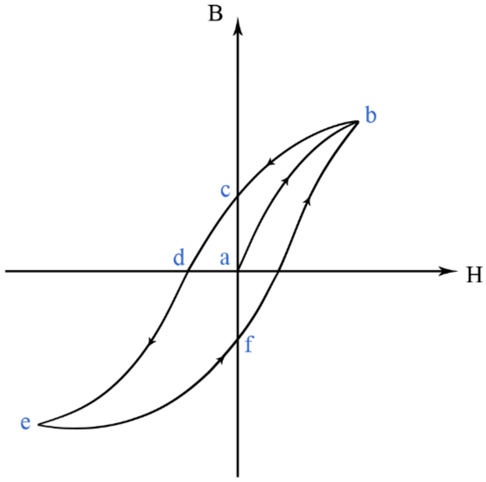


Figure 3 -Typical graph of hysteresis

The basic equation for calculating the total magnetic field is:

$$B = \mu_0 \cdot (H + M)$$

where for our system $\boldsymbol{H}$ is the magnetic field from the coil, $\boldsymbol{M}$ is the magnetization of the magnetic material (magnetic core).
For paramagnetic and diamagnetic materials (different types of magnetic materials but has smaller increases\decreases of the magnetic field) we have a linear relationship between $\boldsymbol{M}$ and $\boldsymbol{H}$:

$$M = \chi_m H$$

Unfortunately, for ferromagnetic materials we do not have linear relationship between $\boldsymbol{M}$ and $\boldsymbol{H}$. But we can via the hysteresis graph extract the value of μ by the relation of $\mu = \frac{\boldsymbol{B}}{\boldsymbol{H}}$ at each point.
The relationship between $\mu, \mu_0, \boldsymbol{\chi_m}$:

$$\mu = \mu_0(1 + \chi_m)$$

But if we are far from the electromagnet, we can approximate the $\boldsymbol{M}$ as linear function of $\boldsymbol{H}$, so we will get $\boldsymbol{M} = \boldsymbol{\chi_m H}$.
The program uses this approximation in the order to calculate the magnetic field strength.

We did not simulate the particle behavior in the human body, because this is a very complicated simulation and a complicated numerical computation. This is by itself another project. Moreover, there are few papers that describe in more depth and experiments about this part [6]. But we will explain the main points here.

There are the three main forces that control the particle behavior:

1) blood advection forces induced by blood plasma convection:

If we will model the behavior of the substance in blood vessel, we will need consider the velocity that the particles have due to blood velocity and the vessel geometry itself. We can model it as a plug flow:

$$v_B = v_{B_{max}}\left(1-\left(\frac{r}{R}\right)^{\zeta}\right)$$

Where $v_{B_{max}}$ is the maximum flow velocity that is at the center of the vessel, r is the radial position of the particle, R is the radious of the vessel and ζ is a parameter that defines the type of profile (in our case a particular type of vessel).
What this equation tells is how the velocity of the particle v_B decreases as its distance from the center of the vessel as result of the composition of the blood.
Moreover, this equation is easier to solve than Navier-Stocks equations.

2) Magnetic drift induced by the applied magnetic field:

Here we have the force that moving the particles and a force that is opposing this motion. The magnetic force on a single particle is:

$$F_{mag} = (m\cdot\nabla)B = \frac{|m|}{|B|}(B\cdot\nabla)B$$

Where $\boldsymbol{B}$ is the magnetic field that the particle feels, $\boldsymbol{m}$ is the magnetic moment of the particle. The second equality is true because that the particles are aligned in the same direction of the magnetic field as result of using superparamagnetic particles (this is the explanation to way the particles will approach to the electromagnets that generate the magnetic field).
By using the Langevin function to represent $\boldsymbol{m}$ and using generalization to represent bunch of particles, we will get [2] :

$$\boldsymbol{F_{mag}} \approx C\cdot\frac{m_{sat}^2}{6\cdot k_B\cdot T}\cdot\nabla(|\boldsymbol{B}|^2)$$

Where $C\left[\frac{number}{m^3}\right]$ represent the concentration of a bunch particles together and it is a function of time and space. m_{sat} is the saturated magnetization of the particle.

The particle will accelerate in the direction of the force until it reaches an equilibrium velocity v_r as result of an opposing force, the "Stocks drag" force:

$$F_{stocks} = 6 \cdot \pi \cdot a \cdot \eta \cdot v_r$$

Where η is the dynamic viscosity of the fluid, a is the hydrodynamic radius of the particle, that is, the radius of the combined iron oxide with the medicine.

3) Diffusion forces induced both by Brownian diffusion and the scattering effect, so we will get that the total diffusion is the sum of both.

The first one is due to thermal fluctuations that makes the particles move randomly, it can be quantified by the diffusion coefficient:

$$D_{\text{Brownian}} = \frac{k_B T}{6 \cdot \pi \cdot a \cdot \eta}$$

The second one is due the collisions between the blood cells with the particles that resulting in scattering, this is also a random motion with diffusion behavior. This is called "shear induced diffusion" [2] The equation for the shear induced diffusion coefficient:

$$D_{shear\ induced} = K_{shear\ induced} \cdot r_{RBC}^2 \cdot \dot{\gamma}$$

Where r_{RBC} is the radius of blood cell, $\dot{\gamma}$ value of the shear rate, $K_{shear\ induced}$ is a coefficient that depends on the blood cell concentration.

The total diffusion can be express as a sum of both the coefficients diffusions:

$$D_{total} = D_{\text{Brownian}} + D_{shear\ induced}$$

We can simulate a group of particles as ferrofluid and then this is a problem of a fluid and not a bunch of particles. So, the equation that represent the concentration of the particles in at point in space as a function of time is:

$$\frac{\partial}{\partial t} C(x, y, t) = -\nabla \cdot [-D_{tot} \cdot \nabla C + C \cdot v_B(y) + C \cdot k \cdot \nabla(|B(x, y)|^2)]$$

Once we understood the theory, we can start to code the software, and construct the electromagnets and the electronic system.

III. Methods

To solve the problem, we constructed a prototype controlled by a micro controller Arduino, and the Arduino is controlled by a software that we developed.
The software sends to the Arduino the data, like frequency and power, and the Arduino controls the electronic system which activates the electromagnets.

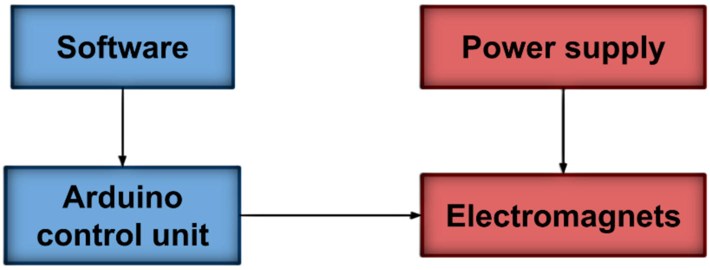


Figure 4 - System diagram of the project

Hardware

In order to develop software-controlled electromagnets, we had to design two different modules: the electromagnets and the control unit.

ELECTROMAGNETS

To obtain the electromagnets, we had to wind wire around a magnetic core. In this task, some parameters must be considered in the design.

- Magnetic core: It is a piece of ferromagnetic material with high magnetic permeability that is used to concentrate the field lines. For this purpose, we choose an iron bar [3] with a radius of $2\ cm$. The radius had to be small enough to concentrate the field, but also wide enough to not saturate the material (also related to the hysteresis).

- Magnet wire: The wire we wind around the magnetic core to carry the current. It is a copper wire coated with a very thin layer of insulation. We choose an 18 AWG wire (diameter $1\ mm$) [4] for a length of approximately $35\ m$. The diameter had to be carefully considered: a too thin wire tends to overhead due to the current, but a thick wire is also a problem, because more are the windings, more the radius is, and weaker the field will be.

- Power supply: While the product we construct is a prototype, we used an adjustable power supply that can deliver up to 10 A. The important parameter here is the current intensity. We do not want to overheat our component, but still we need a strong field. We will talk about how we determined the current intensity below.

CONTROL UNIT

The system is controlled by Arduino. To communicate with the computer, we used the protocol Pyfirmata, which allows us to control the Arduino with Python. We are using two analog pins ($T1$ and $T2$ in the schematic), that provides a voltage between 0 and $5V$. Each of the pin are connected to

1. A led that indicates if a voltage is applied
2. The gate of a MOSFET transistor. The applied voltage opens more or less the transistor.

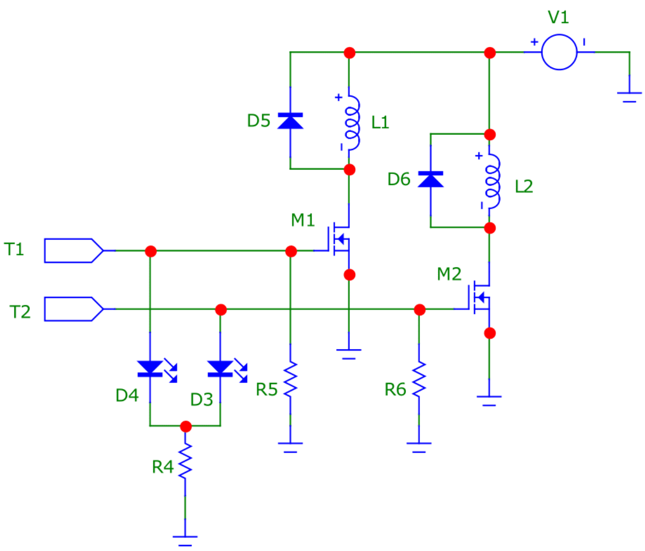


Figure 5 - Schematic of the circuit

The source of each transistor is grounded, and the drain is connected to the electromagnets. For each electromagnet, we connected a diode in parallel to let the coil discharge when it is disconnected.
The two electromagnets are connected to the power supply.
Let us focus on the transistors.
It is a NMOS power transistor [5]. It supports up to $30V$ and $60A$ at room temperature. In the following we will talk in detail about the heat power that the

transistor needs to dissipate. In short, to dissipate the heat, we needed to add two elements:

1. A heat sink that dissipate the heat by transferring it to the surrounding air.
2. Heat-conducting paste that we used to improve heat flow from the transistor to the heat sink.

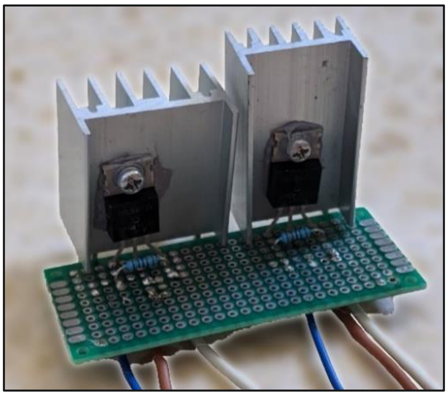


Figure 6 - Mosfet transistors with their heat sink

POWER AND CURRENT COMPUTATION

1. Wire total resistance

   For $35m$ of 18 AWG wire, the resistivity per km is:

   $$\rho = 20.94\left[\frac{\Omega}{km}\right]$$

   So, the total resistance will be:

   $$R = 35 \cdot 10^{-3} \cdot 20.94 = 0.733\ [\Omega]$$

   Experimentally, we got $R_L \approx 0.8 - 0.9\ [\Omega]$ and $R_R \approx 0.9\ [\Omega]$ (where R_L is the resistance of the left electromagnet).

2. Transistor dynamic resistance

   We could not extract the function of the dynamic resistance from the datasheet, but we measured it for $V_G = 5V$

   $$R_{mos} \approx 0.2\ [\Omega]$$

3. Transistor consumption

   Assuming $R_{mos} = 0.2\ [\Omega]$ and the current through the transistor is $I_D = 5\ [A]$,

   $$P = I^2R = 5^2 \cdot 0.2 = 5\ [W]$$

   The thermal resistance is $R_{th} = \frac{100-25}{5} = 15\ °C/W$.

According to the datasheet, the maximum power consumption is $65\ [W]$ at room temperature. Then it is more than enough.

Then, for a current of $5A$, we need a voltage of $V = RI \approx (0.9 + 0.2) \cdot 5 = 5.5\ [V]$, and that's how we got experimentally (see the *result* section).
We also have seen that at $5A$, the electromagnets are slightly heating. The exact power dissipated into each electromagnet is $P = I^2R = 5^2 \cdot 0.9 = 22.5\ [W]$. Thus, each electromagnet is consuming $22.5\ [W]$. The total consumption of all the circuit (non-including the Arduino), when it works at $5A$, is then:

$$P_{tot} = 2 \cdot 22.5 + 5 = 50\ [W]$$

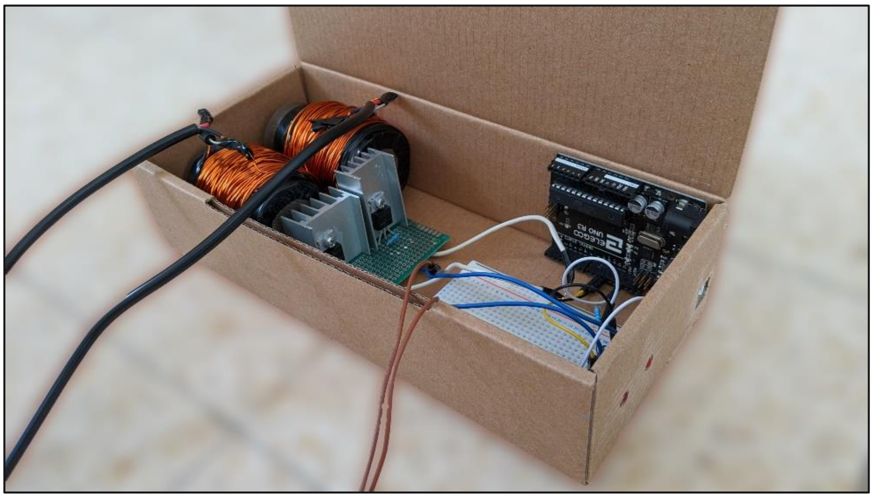


Figure 7 - Photo of the prototype

Software

We write the program in python and using Qt for the graphical user-interface.

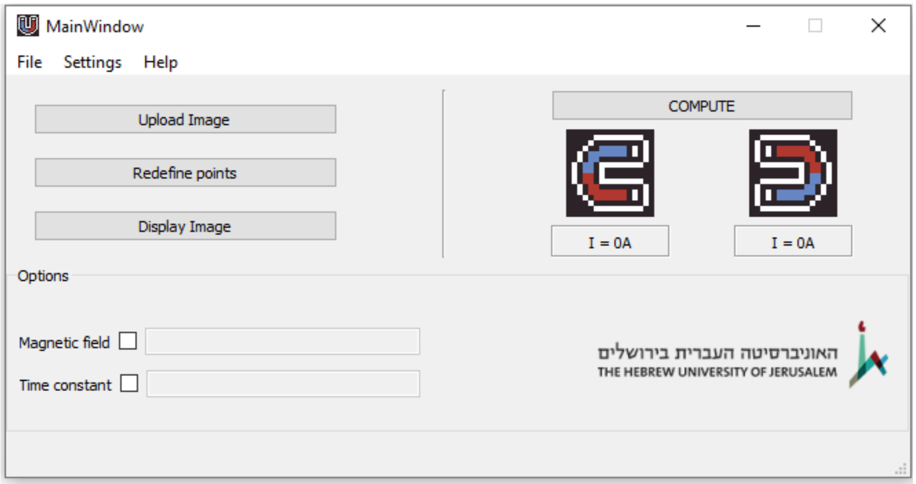


Figure 8 - Screenshot of the program interface

APPLICATION FEATURES

- Uploading an image.
- Marking the disease and the side of the body (no restrictions).
- Ability to define the desirable magnetic field and to define the desirable time constant.
- To show the image with marking that the user made and the shortest path that the program calculated.
- Displaying the calculated currents that will be in each electromagnet.
- A simple system of detection of the Arduino controller by the program itself.
- Changing basic parameters of the electromagnet and the ratio of size between the real world and the image (figure 9).

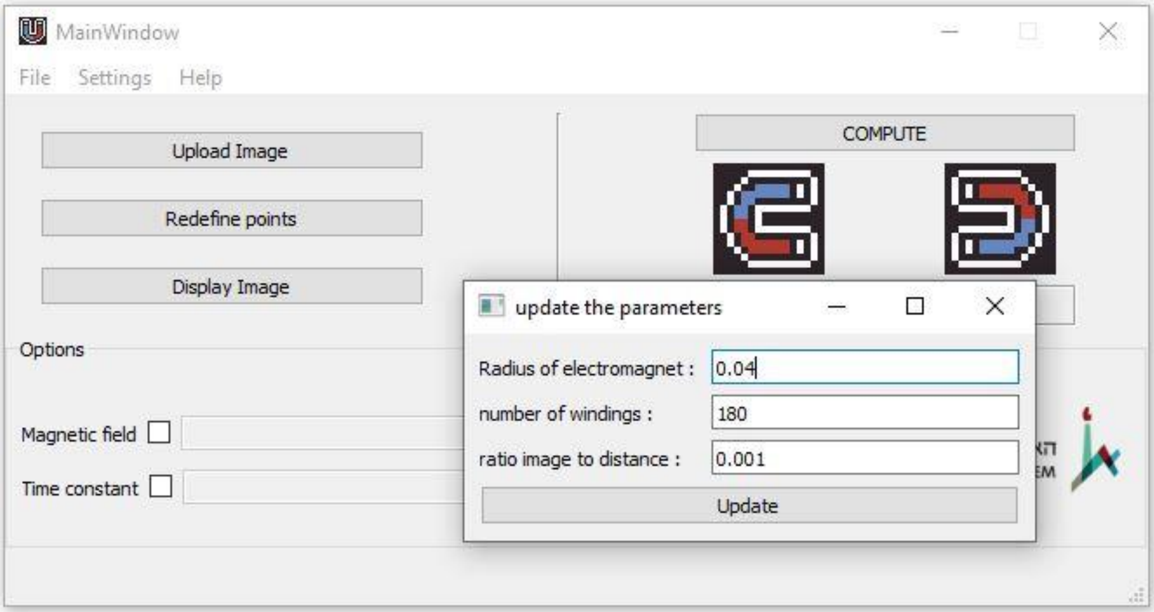


Figure 9 - Updating the parameters in the settings tab

ALGORITHM

We used a simple algorithm to find the minimal path between two sides of the patient body that goes through the disease. It works the follows:

1. Calculate the center of mass of the disease to treat it as a point in 2-dimensional space. This point we donate as c .
2. For each side we want to find a point s_i (where $i = \{1,2\}$ donating a side) from the marked side that form the shortest distance from point c .
3. From 2 points c and s_i we calculate the linear equation cs_i that those 2 points forms. Then we find a point b_i that is on the other side and that is on the line cs_i.
4. We do operations 2 and 3 for both sides. such that we get 2 lines b_2s_1 and b_1s_2 that are close to minimal and we chose the shortest line of them.

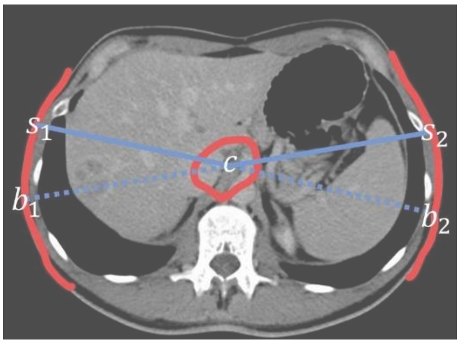


Figure 10 - Illustration of the algorithm

<u>NOTE</u>: It clearly may not be the shortest line, but it is pretty good approximation, and it takes no computational power to apply this algorithm.

APPLICATION FLOW

A basic example of how to use the program so the system will work:

1. The user enters the program and then he chooses a CT scan from his computer directory via the button “Upload Image”.
2. By clicking “Redefine points” button, the user enters a new window where he defines:
    a. Mark one side of the patient body.
    b. Mark the disease.
    c. Mark the other side of the patient body.
3. Clicking “Display Image” button to display the processed image, where the doctor will know where to insert the drug and where to put the electromagnets.
4. Clicking “Compute” button to compute the current needed to achieve the needed magnetic field.
5. By going to the Tab settings, we chose “Upload”, then we simply click “start”, to start the electromagnets to work.

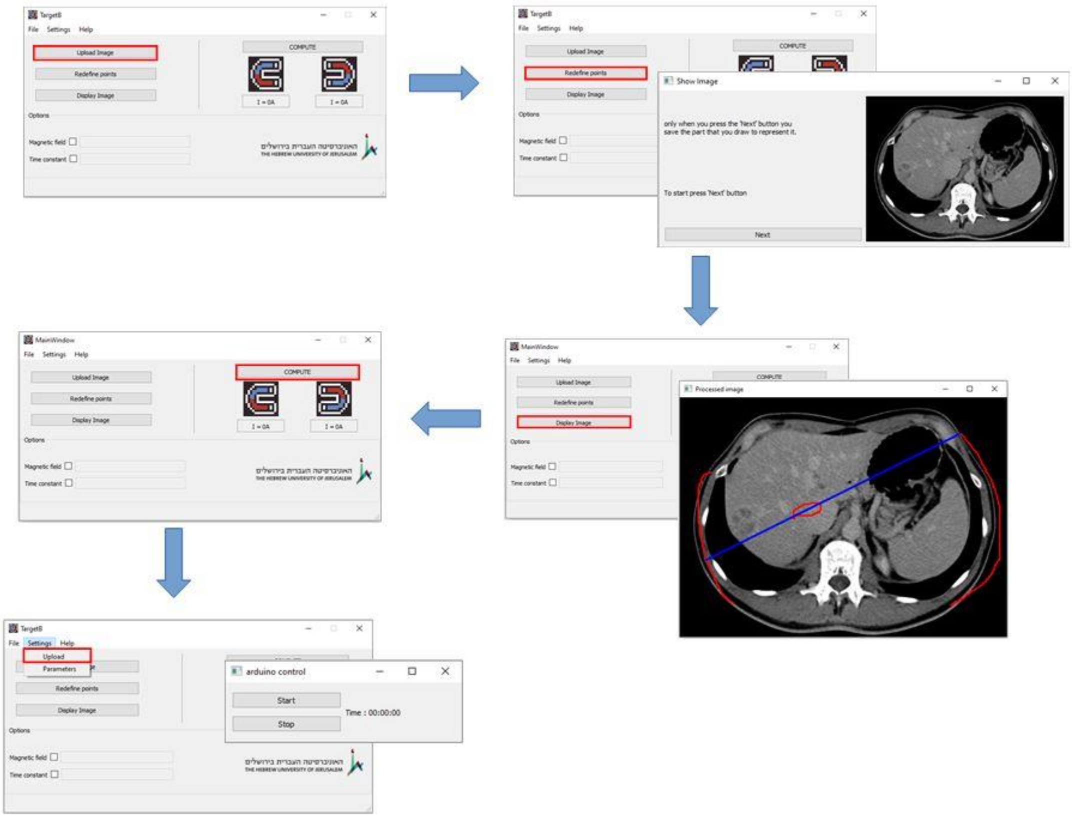


Figure 11 - Application flow

IV. Materials and Equipment

Our solution was to use electromagnets instead of simple magnets. Contrary to simple magnets, with electromagnets you have control over the magnet strength.
With the help of prof Nadav Katz, we build a system of electromagnets that focus the drug in a well-defined zone inside the body.

Power supply

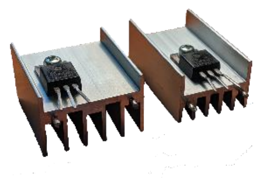
Agilent 6642A power supply. It can deliver a maximum of 20V and 10A, with a power consumption of 200W. It is not the final power supply we well use, it is only more convenient and easier.

Electromagnets

A couple of electromagnets we built. It is made of an iron core (alloy steel round bar 4340), enameled copper wire 18 AWG with 180 windings around each core, electric tape, soldered connection pins.

Transistors

A couple of MOSFET transistors IRF840. We screwed them to heat sink together with thermal paste to enhance the heat dissipation.



Arduino

Arduino Uno is the microcontroller board. It allows us to communicate between the computer and the electromagnets.

V. Results

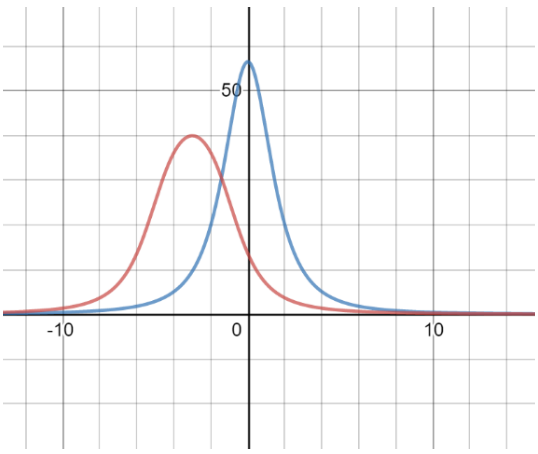
In order to measure the magnetic field created by the electromagnets, we used the Lake Shore Model 425 gaussmeter which provides us a high DC measurement resolution (resolution to 4¾ digits and accuracy of ±0.20%)

Method of measurement

In the theory section, we expressed the field like $B(z) = \frac{\mu_0 n I R^2}{2\cdot(z^2+R^2)^{\frac{3}{2}}}$.

However, **this is wrong**. It only expresses the field from a 2D coil. In three dimensions, this expression in not valid anymore, and we need to integrate it and redefine some parameters. (Still, we do not have to throw away this expression, as we shall see later)

Before going further, we will illustrate our motivation.



Here is an example. The red and the blue graph are almost the same. Except that the blue is for a two-dimension coil, and the red is for a three-dimension coil and is also shifted. However, the number of windings is the same for the two coils. It is only their distribution in space that differ.

The blue graph corresponds to the previous expression, and the red graph is the one we are trying to get.

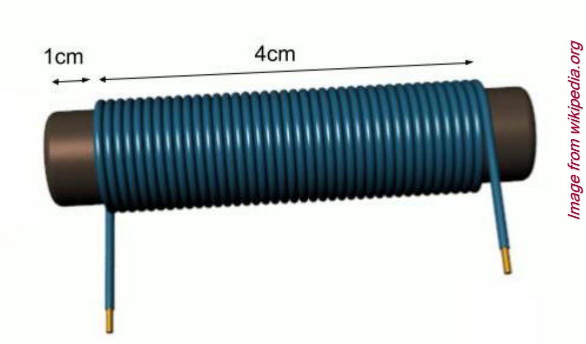
First, let us choose a reference point, let it be x. Our expression becomes:

$$B(z) = \frac{\mu_0 n I R^2 \cdot 10^4}{2 \cdot \left(\left((z+x) \cdot 10^{-2}\right)^2 + R^2\right)^{\frac{3}{2}}}$$

(The units are now in Gauss and in Centimeters)

Now, since the windings are represented in a three-dimensional space, we can make one step further by replacing the number of windings n by the density of windings η.

Experimentally, we measured a gap of $1cm$ between the end of the magnetic core and the start of the coil. We also measured that the coil has a depth of $4cm$.



So, we will define $\eta = \frac{n}{4} = 45 \frac{windings}{cm}$. We assume that the windings are homogenous (it is not really the case, but it simplifies a lot the calculations, and it is a good enough approximation)

By taking the end of the magnetic core as the reference, we could be able to integrate our expression.

$$B_{tot}(z) = \int_{x_1}^{x_2} B(z)\, dx$$

$$B_{tot}(z) = \int_{1}^{5} \frac{\mu_0 \eta I R^2 \cdot 10^4}{2 \cdot \left(\left((z+x) \cdot 10^{-2}\right)^2 + R^2\right)^{\frac{3}{2}}} dx$$

$$B_{tot}(z) = \left[\frac{\mu_0 \eta I R^2 \cdot 10^4 (z+x)}{2R^2 \sqrt{\left((z+x) \cdot 10^{-2}\right)^2 + R^2}}\right]_{x=1}^{x=5}$$

$$\boxed{B_{tot}(z) = \frac{\mu_0 \eta I R^2 \cdot 10^4}{2R^2} \left(\frac{(z+5)}{\sqrt{\left((z+5) \cdot 10^{-2}\right)^2 + R^2}} - \frac{(z+1)}{\sqrt{\left((z+1) \cdot 10^{-2}\right)^2 + R^2}}\right)}$$

Measurements

The graph (11) shows the magnetic field strength in gauss as a function of the distance from the electromagnet (and not from the coil !). We performed two measures, one with the left electromagnet and one with the right one, to ensure the results.

We compared our measurement with:

1. The theoretical field from a two-dimensional modeled coil
2. The theoretical field from a shifted three-dimensional modeled coil

We can expect that the theoretical field from a two-dimensional coil will be stronger than the measured field without magnetic core because all the windings are at the same position and at the origin.

The theoretical field from a shifted three-dimensional modeled coil will be then necessarily weaker, but at least it will give us an infimum, because the real field is amplified by the magnetic core.

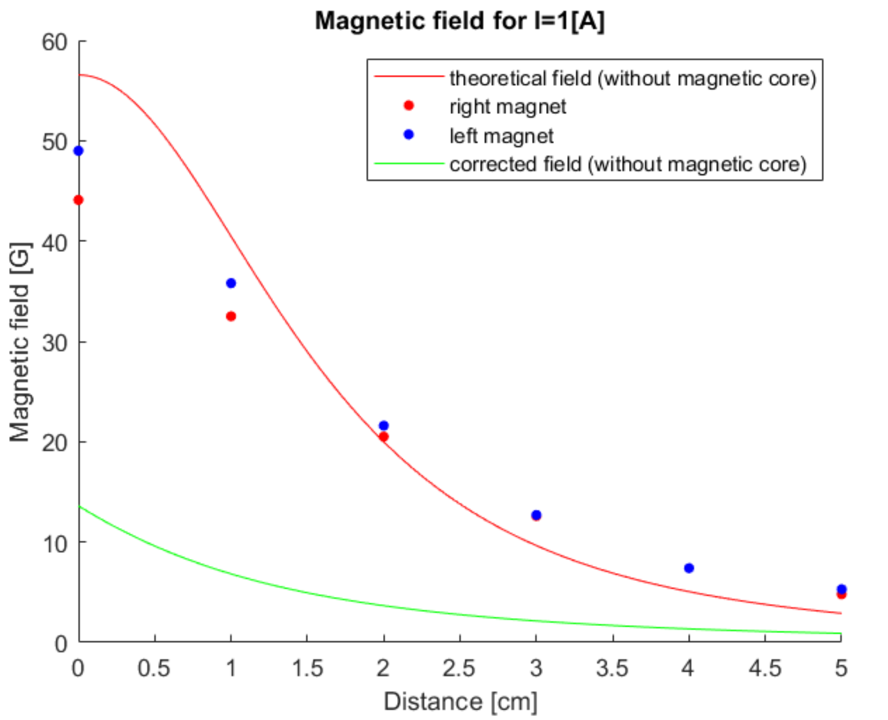


Figure 12 - Graph of the magnetic field versus the distance from the electromagnet

Since there is a non-negligible difference between the theoretical and the measured field, we also wanted to see the theoretical magnetic field when the coil is not shifted (graph 12)

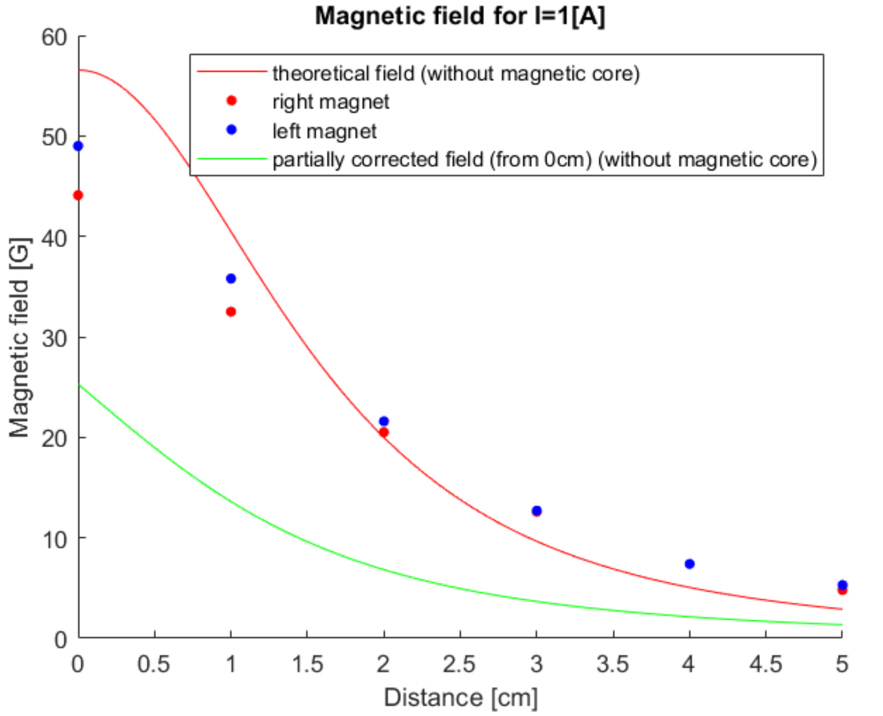


Figure 13 - Graph of the magnetic field versus the distance from the electromagnet

We can see here that the green curve gets closer to the measured data, and that is because of the magnetic core that concentrate the field lines. It is like the coil is starting at $0cm$, and not at $1cm$. However, the field we measured is still stronger because we did not consider the different ways in which the magnetic core impacts on the field.

We can notice that the left magnet is stronger, but as the distance is increasing, it joins the right magnet, certainly because that the windings are not homogenous. Moreover, each coil is winded differently.

⚠ We said earlier that the expression for the 2D coil is wrong. However, we can still use it because that the magnetic core concentrates the field line. Thus, it is like “all the field comes from the end of the core”, as a 2D coil. It is a very bad approximation, but at least it gives us a supremum for the magnetic field.

The next graph (13) shows the magnetic field against the current flowing through the electromagnets. As we expected, it has a linear shape, as long as the field has a linear dependency with the current. The coefficient of the linear fit is $44.92\ \left[\frac{G}{A}\right]$. The fitting is a mean between the blue and the red magnet.

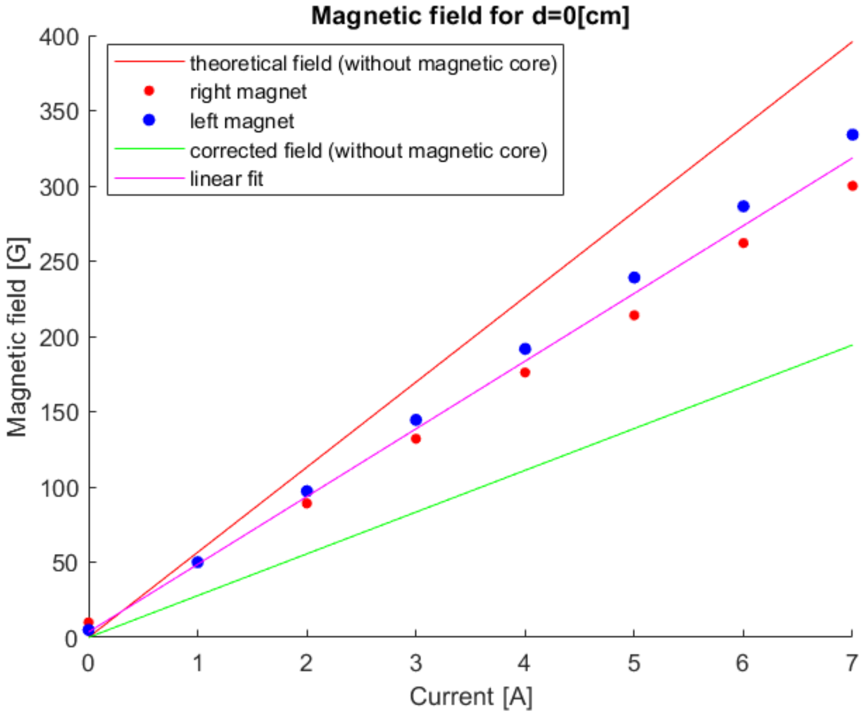


Figure 14 - Graph of the magnetic field versus the current

The next graph (14) shows the magnetic field against the voltage applied on the gate of the transistor. According to the datasheet, the typical gate threshold voltage of the transistor is $1.80\ [V]$. From the threshold, the magnetic field varies linearly.

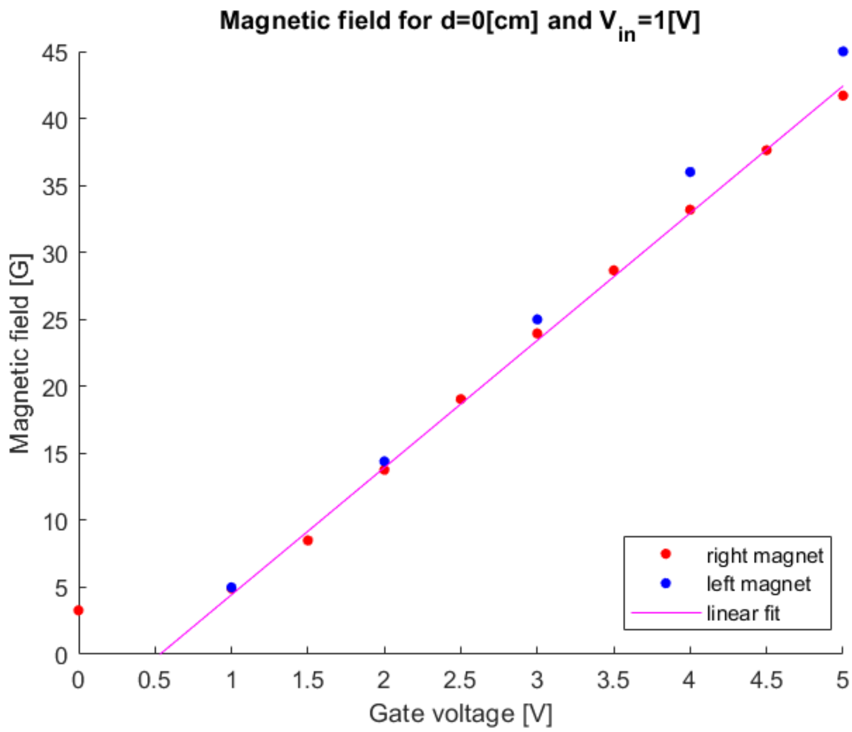


Figure 15 - Graph of the magnetic field versus the gate voltage of the transistor. The coefficient of the linear fit is 9.5

We remind that the magnetic field varies linearly with the current. One could see the dependency of the current with the gate voltage by using the theoretical formula we used before and by isolating the current. We get:

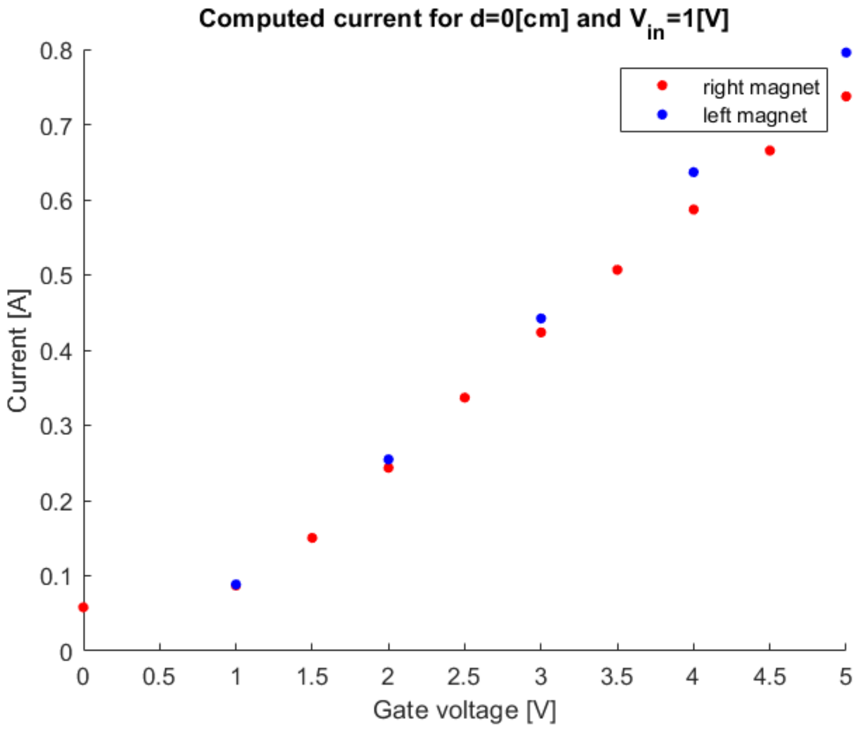


Figure 16 - Graph of the current versus the gate voltage of the transistor

It has indeed the same behavior as the magnetic field.

Proof of concept

In the experiments that we did we can see that we get about $50\ Gauss$ of magnetic field for $1\ A$, so for $5\ A$ we will get about $250\ Gauss$ of magnetic field (this is true because $B \propto I$).

The calculation of this strength are true also in the human body because the magnetic susceptibility of tissue is close to zero, that is χ is somewhere in the region $[10^{-6}, 10^{-4}]$.

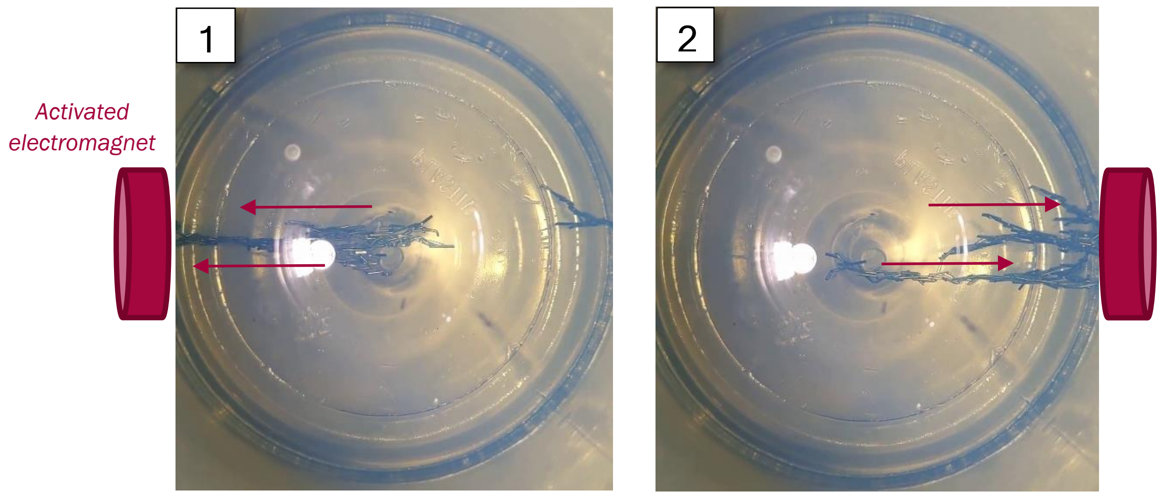
In the lab in Ein-Kerem there was experiments on mouse with weaker magnet and there was shown a movement as result of a near magnet. From this we can say that our electromagnets should work also for small distances. Moreover, there has been done experiments on rats, where there was injected ferromagnetic particles about 250 nm diameter iron-oxide nano-particles, and it was shown that when we move a strong magnet (of about 5000 Gauss) closer to that area, then the particles start to move. Of course, in this experiment the magnet is stronger than our electromagnets, but if we would improve our design then our electromagnets will be strong enough for this.

As the software take into account the ratio of the distance in the image and in the real world, then the program can make a precise calculation of distance between two points, while the precision depends on the resolution of the image. The magnetic field that the program is calculating is pretty the same as the real magnetic field that being created by the electromagnets that we build. This we can see from the graphs above in figure 11, we only need to multiply by a factor.

EXPERIMENT

We set up a small experiment to test the electromagnets in action. We used an hydroalcoholic hand gel bottle (thank you Covid-19) to simulate the body, with one electromagnet at each side of the bottle, on the same axis. To mimic the paramagnetic particles, we used stapler staples cut in small pieces.

Objective: to show that the particles could be attracted by the electromagnets inside the body in order to focus them in a well-defined area.



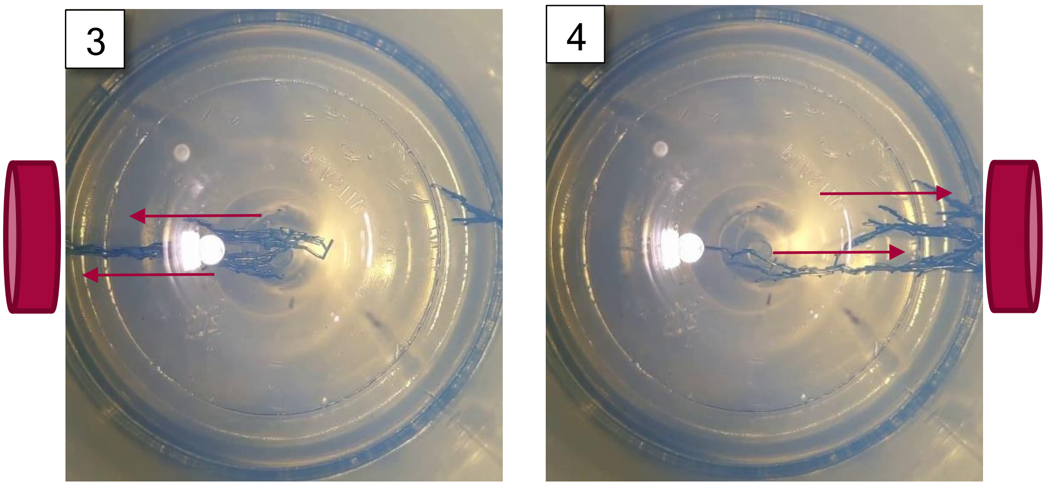
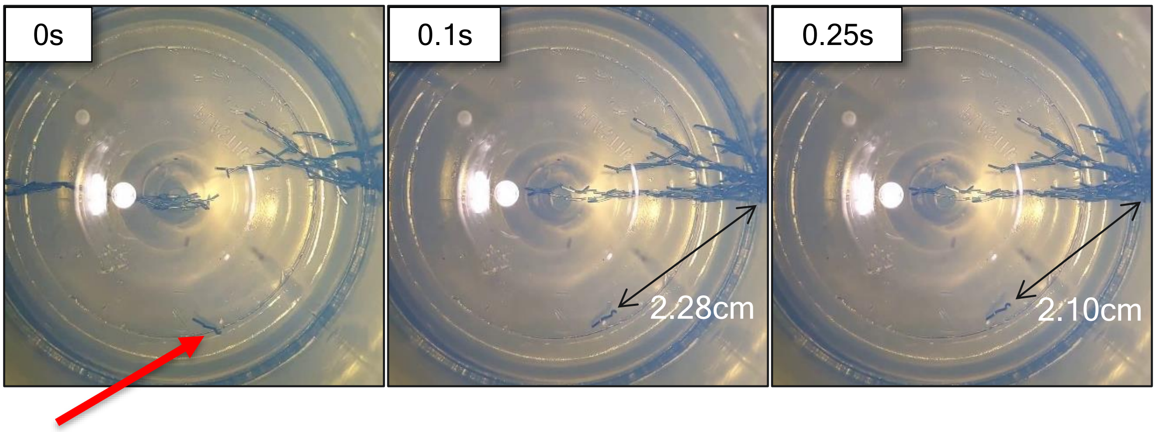


Figure 17 - Photos of the experiment at four different phases

Main drawback of this experiment: The stapler staples are much heavier and bigger than the nanoparticles, fall in the bottom of the bottle and agglomerate in cluster.

Conclusions and issues: Once the particles are attracted by one electromagnet, sometimes they do not come back, because the field is too weak at such distances. One possible solution is to modulate the field to make it decrease with time with an exponential rate. In this way, the power is at his maximum when the particles are far from the electromagnet, and minimum/off when the particles are close. However, to do that, we need precise simulations and calculations, or a real-time monitoring. In this experiment, we were not able to focus the staples in a specific area.

Pros: We were able to control the power of each electromagnet and the frequency through the software. The staples that were not on the electromagnet axis were also attracted back to the axis (see figures below).



VI. Conclusions

The challenge in this project was to build from scratch a complete system composed by a computer program and an electrical system that operate together to provide the desired response.

In general, in an engineering design process, engineers apply mathematics and sciences such as physics to find novel solutions to problems or to improve existing solutions [11].
For the physics, we had to understand the properties of the magnetic field, how the generate it and how to manipulate it. We also had to design and build the electromagnets, build the electronic system.
We also had to develop the software whose task is to compute the control parameters for the electromagnets according to the requirements. It had to be reliable, user-friendly, and efficient.

We also choose to build electromagnet instead of using existing ones. Indeed, we could not find suitable product on the market for our project, and it was much more enriching and smarter to build new ones.

The measurements we performed showed that we are able to totally control the field on the axis of the electromagnets, their intensity and their frequency, in such a way that we could focus the ferromagnetic particles in a well-defined area.

Summary of Achievements

- Development of a software including a GUI and a control system.
- Design and construction of reliable electromagnets.
- Design and construction of the electronic system of the electromagnets.
- Implementation of the communication system between the electromagnets and the computer.
- Laboratory measurements of the system and verification.

METHOD LIMITATIONS

We can see that we have few limitations:

1. The magnetic field is not strong enough.
2. Our prototype consists of 2 electromagnets so we can control the movement of substance only in one axis, so the diffusion of the substance in the human body can happen in the two other axis.
3. We assume that the doctor will insert the medicine in the point where the program calculated it to be inserted. Sometimes it is complicated to get to this area in the human body, and it is not grantee that the doctor will insert the medicine in the right place.
4. We cannot clearly demonstrate the effect of the magnetic core on the strength of magnetic field because we did not measure the magnetic field of the electromagnet without the magnetic core.

PROPOSED ENHANCEMENTS

- We could see that in our case we did not achieve a high amplitude of the magnetic field, the more strength we have we can reach the disease that is deep in the human body.
- More stability in more axis in space, that is to add more electromagnets (a configuration of 4 electromagnets) so that the substance will diffuse to less directions and much slowly.
- The program will by itself determined the placement of the disease and the side of the body on the CT image (to achieve this , we need to add and build a machine learning to the program that is trained on a lot of CT scans).
- To make the electromagnets smaller and more portable. That is, we want to make in the end a belt that consists of electromagnets so the patient could move when he is in treatment, and of course that is more comfortable.

In the future, this type of therapy will allow cancer treatment without side effects. But we would also imagine that this method will allow us targeted treatment for all kinds of diseases

Useful links

Project website: https://targetb.wordpress.com/

Presentation video: https://youtu.be/a6feZAbdhC0

Experiment video: https://youtu.be/NnRVpnlX9iE

Electromagnets demo: https://youtu.be/1jpI8D4voAA

GitHub repository: https://github.com/HUJI-T610/TargetB/

Bibliography

[1] Marcus, M., Smith, A., Maswadeh, A., Shemesh, Z., Zak, I., Motiei, M., Schori, H., Margel, S., Sharoni, A., & Shefi, O. (2018). Magnetic targeting of growth factors using iron oxide nanoparticles. *Nanomaterials*, *8*(9). https://doi.org/10.3390/nano8090707
(this article discusses the magnetic targeting of growth factors, not tumors. The matching article has not been published yet)

[2] Nacev, A., Beni, C., Bruno, O., & Shapiro, B. (2011). The behaviors of ferromagnetic nano-particles in and around blood vessels under applied magnetic fields. *Journal of Magnetism and Magnetic Materials*, *323*(6), 651-668. https://doi.org/10.1016/j.jmmm.2010.09.008

[3] AISI 4340 Allow Steel https://www.azom.com/article.aspx?ArticleID=6772

[4] Wire Gauge and Current Limits https://www.powerstream.com/Wire_Size.htm

[5] Power MOSFET irlb8721 datasheet http://hackstore.co.il/wp-content/uploads/2016/09/irlb8721pbf.pdf

[6] Grief, A. D., & Richardson, G. (2005). Mathematical modelling of magnetically targeted drug delivery. *Journal of Magnetism and Magnetic Materials*, *293*(1), 455–463. https://doi.org/10.1016/j.jmmm.2005.02.040

[7] Wu, M., & Huang, S. (2017). Magnetic nanoparticles in cancer diagnosis, drug delivery and treatment (Review). *Molecular and Clinical Oncology*. https://doi.org/10.3892/mco.2017.1399

[8] Transistor heat dissipation https://dlb.sa.edu.au/rehsmoodle/file.php/466/kpsec.freeuk.com/heatsink.htm#:~:text=Waste%20heat%20is%20produced%20in,it%20to%20the%20surrounding%20air

[9] Thermal resistance https://www.mouser.com/pdfdocs/TEN10-000-012_ThermalResistance_FAQ.pdf

[10] On-Axis Field of a Finite Solenoid https://tiggerntatie.github.io/emagnet-py/solenoids/solenoid.html

[11] https://en.wikipedia.org/wiki/Engineering