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FACULTY OF ELECTRICAL ENGINEERING
DEPARTMENT OF MICROELECTRONICS

Miniature System with Electromagnetic Levitation

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ZADÁNÍ DIPLOMOVÉ PRÁCE

Student: **Bc. P U C I Florian**

Studijní program: Komunikace, multimédia a elektronika
Obor: Elektronika

Název tématu: **Miniaturní systém s elektromagnetickým vznášením**

Pokyny pro vypracování:

1. Proveďte rešerši současného stavu poznatků řešení miniaturních systémů s řízeným elektromagnetickým vznášením rotoru.
2. Navrhněte a realizujte model jednoduchého miniaturního systému s řízeným elektromagnetickým vznášením rotoru, pro návrh využijte vhodný princip uváděný v literatuře. Pro realizaci statorové části využijte systém vodičů na desce plošného spoje, jako rotor využijte permanentní magnet nebo soustavu buzených cívek. Řízení pohybu rotoru realizujte elektronicky (s využitím mikroprocesoru, logických obvodů, popř. řízení počítačem).
3. Vyhodnoťte dosažené parametry, navrhněte možné úpravy pro jejich zlepšení.
4. Proveďte ekonomickou rozvahu pro komerční využití navrženého modelu.

Seznam odborné literatury:

[1] Novotný, K.: Teorie elmag. pole I. Skriptum, ČVUT Praha, 1998
[2] http://www.phy.uct.ac.za/courses/phy110w/W_Mag_2.pdf
[3] http://www.usna.edu
[4] http://www.hk-phy.org/articles/maglev/maglev_e.html

Vedoucí: **Prof.Ing. Miroslav Husák, CSc.**

Platnost zadání: 31. 8. 2015

L.S.

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děkan

V Praze dne 28. 1. 2014

Abstract

The major objective of this master thesis is the design and construction of a contactless, magnetically levitated planar actuator, with moving magnets. The translator of these planar actuators is levitated above the platform with no support other than the magnetic field created from the stator part. As a translator is used either a disk permanent magnet or a uniform shaped object with the center of mass coincident with the center of geometry. This is embedded with 4 stabilizing permanent magnets on every corner so that it can provide sufficient control force against the lateral forces and with another permanent magnet on the bottom of the carrier to counteract the weight of the carrier. The stator part is represented by four blocks with 4 coils each, giving in total 16 partially identical coils and a microcontroller board for positioning control of the translator. The aim of the stator design is the arrangement of the cylindrical solenoids and their floating currents, which are controlled by PWM signals, in such a way, so together would form a uniform magnetic field over a planar surface slightly above the coil array. As only the coils located in the stator part can produce significant force and torque, the current through the coils is switched during the movements of the translator in the xy-plane.

Abstrakt

Hlavním cílem této diplomové práce je návrh a konstrukce miniaturního systému fungujícího na principu magnetické levitace. Rotor je vznášen nad plošnou plochou pouze při působení magnetického pole, vytvořené ze statorové části systému. Jako rotor se obvykle používá buď permanentní magnet nebo objekt s jednotným tvarem, ve kterém je těžiště shodné s centrem geometrie. V daném objektu jsou vloženy čtyři stabilizační permanentní magnety, jeden v každém rohu, aby bylo možné zajistit dostatečnou kontrolu síly proti příčným silám, a další permanentní magnet na spodní části translatoru, který se používá k vyrovnání hmotnosti rotoru proti gravitační síle. Statorová část se skládá ze čtyř bloků se čtyřmi cívkami, takže celkem šestnáct stejných cívek a z mikrokontroléru, jehož hlavním úkolem je řízení polohy rotoru. Hlavním cílem konstrukce statoru je uspořádání válcových solenoidů a řízení jejich plovoucích proudů, které jsou ovládány pomocí PWM-kových signálů, a to takovým způsobem, aby společně všechny cívky vytvořily homogenní magnetické pole nad rovinnou plochou. Pouze cívky, které jsou umístěné ve statorové části mohou způsobit významnou sílu a moment. Proud cívkami je přepnutý během pohybu translatoru v rovině xy.

Statement of Originality

I hereby declare that I entirely wrote this master thesis. All the information has not been previously published or written by another person, with the exception of the references, mentioned in the text. The bibliography is added as a separate part at the end of this thesis. I am fully responsible for the content of this master thesis and I certify that this thesis does not infringe the rights of the third party. I also certify that this is an original copy of my master thesis.

In Prague day ....

(author's signature)

Prohlášení

Prohlašuji, že jsem zpracoval tuto magisterskou práci samostatně a s pomocí mého vedoucího práce. Všechny informace nebyly dříve publikovány jinou osobou, s výjimkou odkazů, uvedených v textu. Bibliografie je přidáná jako samostatná část na konci této práce. Jsem plně zodpovědný za obsah této magisterské práce, a potvrzuji, že tato práce neporušuje práva třetích stran.

V Praze dne ....

(podpis autora)

Acknowledgement

I sincerely would like to express my gratitude to my supervisor, Prof. Ing. Miroslav Husák, CSc. for giving me the opportunity to write this thesis, with his continuous and very helpful consultations and devoted control with the purpose of, that my diploma thesis will benefit according to the academic requirements.

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Poděkování

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Také velmi zvláštní poděkování patří mým rodičům za jejich neustálou podporu a pomoc během celé doby, při které byla tato práce napsána.

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List of symbols and shortcuts

MagLev	-	Magnetic Levitation
V	-	Electric voltage, unit [V]
I	-	Electric current, unit [A]
E	-	Electric field, unit [Vm^{-1}]
q	-	Electric charge, unit [C]
μ_0	-	Free space permeability, unit [Hm^{-1}]
ε	-	Permittivity of the medium, unit [Fm^{-1}]
r	-	Radius of the conductor, unit [m]
B	-	Magnetic field, unit [T]
F	-	Force of the magnetic levitation, unit [N]
d	-	Distance between the centers of the wires, [m]
R	-	Electrical resistance, unit [Ω]
l	-	Length of the conductor, unit [m]
f	-	Frequency, [Hz]
DOF	-	Degree-Of-Freedom
HPPA	-	Herringbone Pattern Planar Actuator
N	-	The North pole of the magnet
S	-	The South pole of the magnet
AC	-	Alternative Current
EMS	-	Electromagnetic Suspension

EDS	-	Electrodynamic Suspension
LIM	-	Linear Electric Motor
PCB	-	Printed Circuit Board
CZK	-	Czech Crown, the Czech Republic currency
Vin	-	Input voltage
GND	-	Ground pin
USB	-	Universal Serial Bus
IOREF	-	Input/Output Voltage Reference
SRAM	-	Static Random-Access Memory
EEPROM	-	Electrically Erasable Programmable Read-Only Memory
TX	-	Transmitting pin
RX	-	Receiving pin
PWM	-	Pulse Width Modulation
SPI	-	Serial Peripheral Interface
MISO	-	Master Input Slave Output
MOSI	-	Master Output Slave Input
AREF	-	Analog Voltage Reference
ICSP	-	In-Circuit Serial Programming
DTR	-	Data Terminal ready

1. Chapter: Introduction

The aim of this master thesis is the design and construction of a system working on the principle of magnetic levitation. The term refers to objects that rise or float when magnetic forces are involved. A well-known application of this technology, are of course the maglev trains, but this is not the only one, here we can mention the usage in medicine, i.e. helping the blood to circulate in human chests, measurement of fine dimensions with subatomic resolution; in industry, i.e. for melting and mixing the reactive high-temperature metals; other like cooling our laptops, helping in invention of integrated circuits with multimillion-dollar photolithography systems, etc. But, despite of the fast development of this technology, there are still a lot of questions that need to be answered. Some of them concerning about basic principles, applications, pros and cons of applied solutions, circuit design, stabilization, etc., can find an answer in this master thesis.

This master thesis concludes with the construction and verified functionality of the final sample, which will be a moving-magnets planar actuator. There exist two types of planar actuators, either with moving coils and stationary magnets, or moving magnets and stationary coils. But the samples of both these categories consist of two main parts, the translator and the stator platform. In the case of this thesis, the translator part is represented by a uniform shaped object with the center of mass coincident with the center of geometry. This is embedded with four stabilizing permanent magnets on every corner so that it can provide sufficient control force against the lateral forces and with one permanent magnet on the bottom of the carrier to counteract the weight of the carrier. In the stator part there are 16 partially identical handmade coils, forming together a 4x4 array. The current which flows through a relevant coil in the stator is controlled from the output PWM signal of one of the pins of the microcontroller board Arduino Mega 2560. As the output pin current is limited to 40mA, which means very weak magnetic field around the coil, for this purpose are constructed 4 external circuits with power MOSFET transistors. The coils themselves are supplied by an external supply source. The stator needs to be powered and cooled continually in order to achieve the proper functionality conditions.

The second chapter of this thesis explains the fundamentals of the electromagnetic theory and also gives some definitions in order to firstly understand the functionality of the device from the theoretical point of view. In the following Chapter 3 is given a brief overview of magnetic levitation, what forces that cause the levitation of the objects and what forces are used to compensate it, etc. Further Chapter 4 gets more into the details of this technology, explained further by applications and projects from the reality, the advantages and the disadvantages of each solution, etc. Then, Chapter 5 is an introduction to the planar motors, the two basic configurations for their construction, either with moving magnets or with moving coils, comparison between these topologies, possible configurations, etc. This chapter is like the entrance gate to understand the schematic diagram, design, used components needed to construct the device, solutions that were experimented, different problems and issues till the final test, float diagram of the programming code, etc. described in details in Chapter 6. In the following Chapter 7 will be discussed the accomplished results in this thesis, some of the problems during the design and a few recommendations for future projects. Chapter 8 gives the economic representation of the constricted device. In the last part of this thesis, Chapter 9 will be discussed conclusions of the research and the functionality of the device, its limitations, usage conditions, and as well some recommendations for future projects.

2. Chapter: Basics of magnetism

Magnetism is a term used to define the force of attraction or repulsion that operates at a distance between two magnets or magnetized materials. The field that is created near these objects is called a magnetic field and is caused by electrically charged moving particles. Magnets have two poles, called the north (N) and south (S) pole. Two magnets will be attracted by their opposite poles, and each will repel the like pole of the other magnet. Moving or spinning of the electrically charged particles mentioned above, form imaginary lines of flux which create the magnetic field. Simple examples are the spin of a proton and the motion of electrons through a wire in an electric circuit.

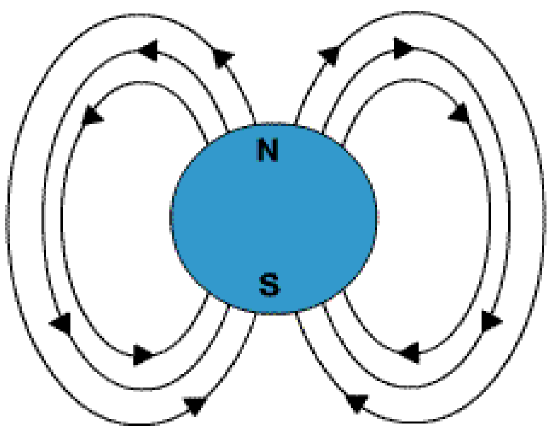

Figure 1. Magnetic field or lines of flux of a moving charged particle [1]

As it is visible from the Fig. 1, the lines of magnetic flux flow from one end of the object to the other. It has come to a decision between the scientists that one end of a magnetic object is called the N or North-seeking pole and the other, the S or South-seeking pole, as related to the Earth's North and South magnetic poles. The magnetic flux is defined as the trajectory of the charged particle from N to S. [1]

2.1 Magnetic force. Attraction. Repulsion

The magnetic field created around an object can create a magnetic force on other objects that have around them magnetic fields as well. That force is what we call magnetism. When the magnetic field is applied to a moving electric charge, such as a moving proton or the electrical current in a wire, the force on the charge is called a Lorentz force.

Attraction

When two magnets or magnetic objects are close to each other and their different poles are facing each other, there is a force that attracts the poles together, as shown in Fig. 2.

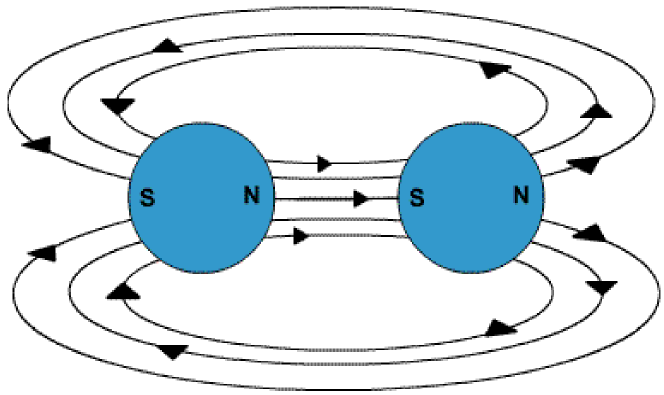

Figure 2. Force that unlike poles N and S attract each other [1]

Repulsion

When two magnetic objects have same poles facing each other as shown in Fig. 3, the magnetic force pushes them apart. [1]

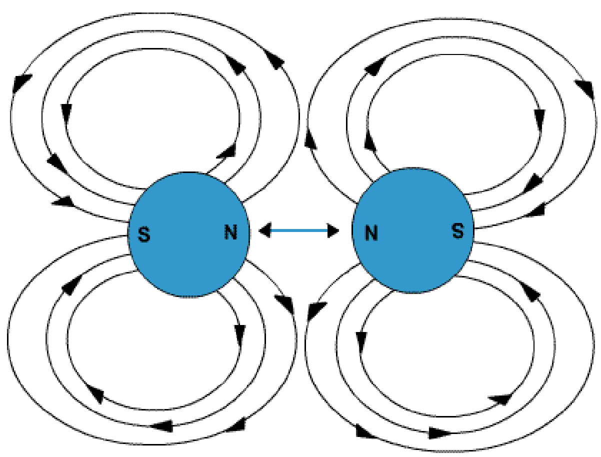

Figure 3. Force that like poles N and N repel each other [1]

2.2 Magnetic field due to current

Magnetic effect can be evaluated as one of the major effects of electric current in use. A current carrying conductor creates a magnetic field around it, which can be comprehended by using magnetic lines of force or magnetic flux lines. The nature of the magnetic field lines around a straight current carrying conductor is concentric circles with center at the axis of the conductor. The direction of the magnetic field lines of force around a conductor is given by the Maxwell's right hand grip rule or the right handedcork screw rule as shown in the following picture.

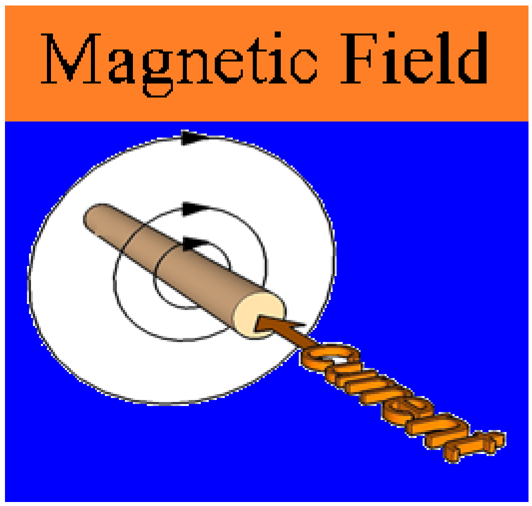

Figure 4. Direction of the magnetic field [2]

The strength of the magnetic field created depends on the current through the conductor. Here is important to mention that exist different shapes of conductors such as a wire, a solenoid, a circular loop, etc. If the conductor is a circular loop, the loop behaves like a magnet. If the current in the loop has the anticlockwise direction, a north pole is formed and if the current has the clockwise direction a south pole is formed. A very common and easy way of finding the direction of magnetic field consists of these simple steps. Step 1: hold a current-carrying straight conductor in your right hand such that the thumb points towards the direction of current. Step 2: then your fingers wrap around the conductor. This the direction of the field lines of the magnetic field. This is known as right hand thumb rule**.** [2]

Magnetic field around a straight wire

For the electric field we can write:

$$dE = \frac{1}{4\pi\varepsilon}\frac{dq}{r^2} \tag{1}$$

which can be written in a vector form as follows:

$$d\vec{E} = \frac{1}{4\pi\varepsilon}\frac{dq}{r^2}\vec{r} \tag{2}$$

This above description is shown in the following Fig. 5.

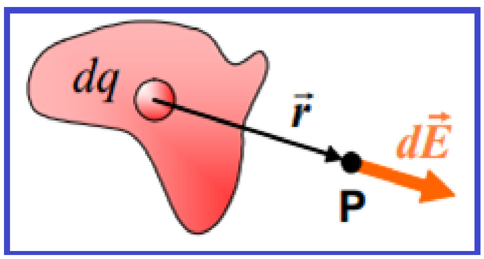

Figure 5. Electric field due to a certain charge distribution [3]

If we use a current length element, $i\overrightarrow{ds}$ with a current distribution similar to a wire as shown in the Fig. 6.

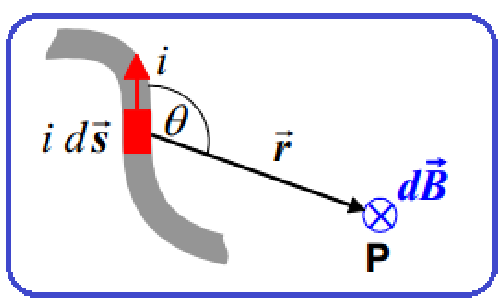

Figure 6. Usage of the current-length element [3]

we can derive the same equation applicable for magnetic field - the Biot-Savart law:

$$dB = \frac{\mu_0}{4\pi}\frac{i\overrightarrow{ds} \times \vec{r}}{r^3} \tag{3}$$

The magnitude of this distribution can be calculated as follows:

$$dB = \frac{\mu_0}{4\pi}\frac{ids\, sin\theta}{r^2} \tag{4}$$

By using the symmetry that every current element $i\overrightarrow{ds}$ in the upper half of the wire has a corresponding element in the lower half causing the same field at P, as shown in the Fig. 7,

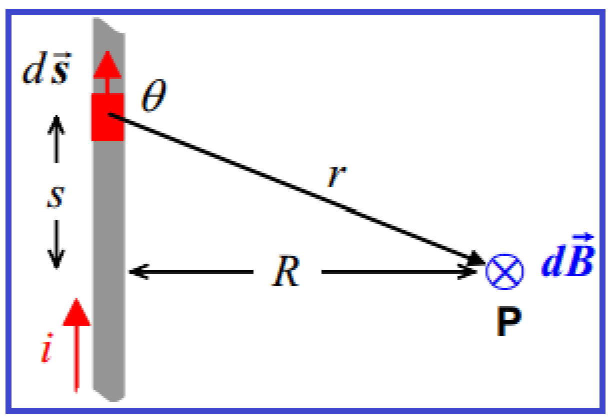

Figure 7. The magnetic field at point P due to a current-carrying wire [3]

and adding the substitution for $sin\theta = \sin(180 - \theta)$ and $r = \sqrt{s^2 + R^2}$ and integrating from 0 as the lower border to ∞, a well-known and simplified equation follows [4]:

$$dB = \frac{\mu_0}{2\pi}\frac{i}{R} \tag{5}$$

<u>Magnetic field in a circular wire</u>

By using the Biot-Savart law, the field at point P due to a differential current element $i\overrightarrow{ds}$ shown in Fig. 8.

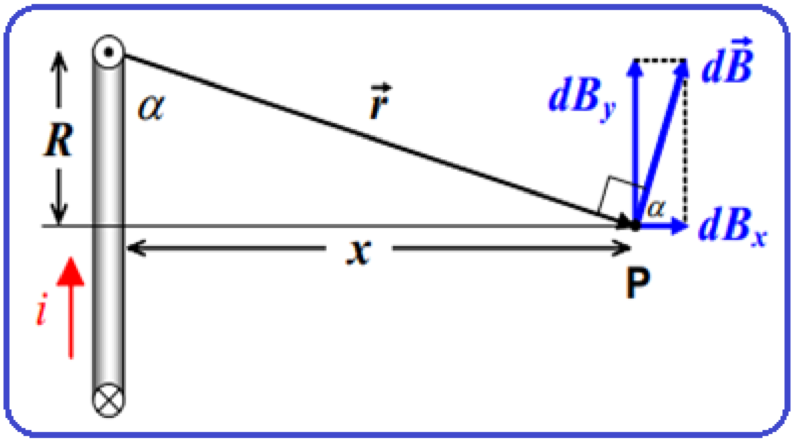

Figure 8. The magnetic field at point P due to a circular wire [3]

is given by the following equation:

$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{i\vec{ds}}{(R^2+x^2)} \quad (6)$$

Applying that all the components perpendicular to the axis (dB_y) sum to zero, so we need consider only dB_x, i, R and x have the same values for all elements around the loop and while integration the integral $\int ds$ is just 2πR, we get the final equation [4]:

$$Bx = \frac{\mu_0}{4\pi}\frac{iR^2}{(R^2+x^2)^{3/2}} \quad (7)$$

3. Chapter: Magnetic levitation technology

3.1 What magnetic levitation means. Definition

Magnetic levitation, also known as Maglev, nowadays has become a familiar terminology. Mainly it refers to objects that rise or float above the platform when magnetic forces are involved. A very popular application, of course, are maglev trains. Further on, a simple example showing a form of magnetic levitation. First step is sending equal current in opposite directions through two parallel wires, one of which is in fixed position. The non-fixed wire will rise as the current increases, which shows that there exist a force that creates this levitation.

Each of us have heard or tried these kinds of experiments where, in addition to magnetic levitation, magnets (apparently) exert a push or a pull on objects made of iron, such as a paper clip. The true fact concerning about all of these types of situations is as follows: *The force that lifts a train or wire, or pulls a paper clip to a magnet, is not only a magnetic force.*

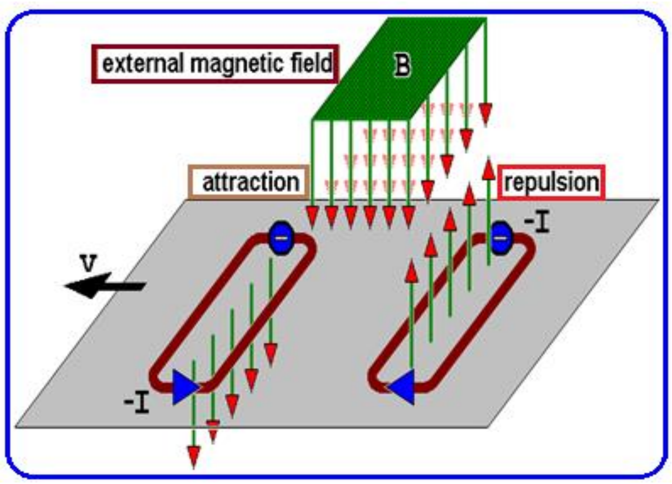

Figure 9. The magnetic levitation [4]

A very simple explanation: the magnetic force acts on moving charges (usually the electrons) and not on the material. It is this group of moving charges that cooperates with the material via the electric force. The statement that a magnetic force "lifts" or "pulls" can create the misconception that a magnetic force can do work. But the result is very surprising; a magnetic force never does work. The reason is that a magnetic field never changes the *magnitude* of the velocity (i.e., speed) of a moving charge, even though it may change the charge's *direction* of motion! Consequently, the force that lifts a train or pulls a paper clip to a magnet cannot be a magnetic force. Of course, magnetic forces are involved and are often equal to the actual lifting or pulling force. However, it is always an electric force that lifts a train or wire. [5]

A simple schematic is shown in the following Fig. 10.

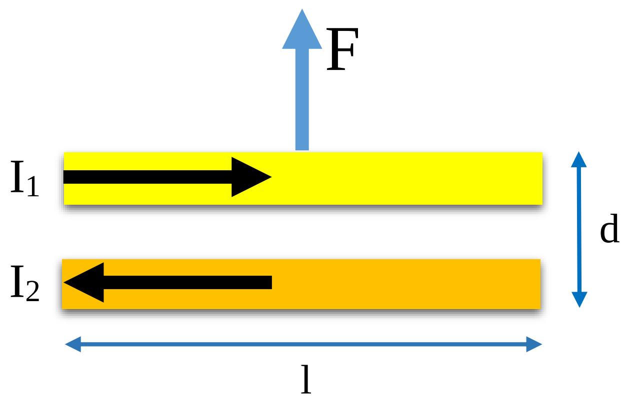

Figure 10. Force of the magnetic levitation [5]

The magnitude of the force, |**F**| = *F*, on a length *l*, can be calculated as follows:

$$\frac{F}{l} = \frac{\mu_0}{2\pi}\frac{I_1 I_2}{d} \quad (8)$$

The parameter *d* is the distance between the centers of the wires. In this simple experiment, we can define that both, the upper and lower bars are part of a series circuit. Thus, the magnitudes of the currents are equal (i.e., $I_1 = I_2 = I$). The equation (1) can be simplified:

$$\frac{F}{l} = \frac{\mu_0}{2\pi}\frac{I^2}{d} \quad (9)$$

3.2 The Eddy currents

An eddy current is the term used for the current that is induced in little swirls ("eddies") on a large conductor. This can be explained by this simple experiment. A large conductive metal plate, which intersects perpendicularly to the sheet, is moved through a magnetic field.

This will cause the magnetic field to induce small "rings" of current which will actually create internal magnetic fields opposing the change. This is the reason why a large sheet of metal moving through a strong magnetic field will stop as it starts to interact with the field. The whole kinetic energy of the metal plate will cause a major change in the magnetic field as it enters it. This will induce rings of current which will oppose the surrounding magnetic field and slow the object down. The kinetic energy will be used for driving small currents inside the metal. This energy will turn into heat as these currents push through the metal.

Likewise, another example is that while pushing a wire loop into a magnetic field will induce such a current which will make it difficult to continue pushing. Also it will resist being pulled out as well. An eddy current has the same principle but instead of being forced in the path of the loop, it is allowed to travel in the "Eddy" pattern.

To avoid the eddy currents, it is recommended that the long metals should be cut in to small pieces so that large eddies cannot occur. This is why small laminations with an insulator in between are used to cover the metal cores of transformers. This will prevent the AC energy from being lost to eddies generated within the magnetic core.

But, sometimes eddy currents are a good thing because they can help to turn kinetic energy quickly into other forms of energy. Recently, the braking systems are being built in a similar principle. Adding a magnetic field around a spinning piece of metal will cause eddy currents in that metal to create magnetic fields which will slow the object spinning down quickly as long as the magnetic is strong enough. [6]

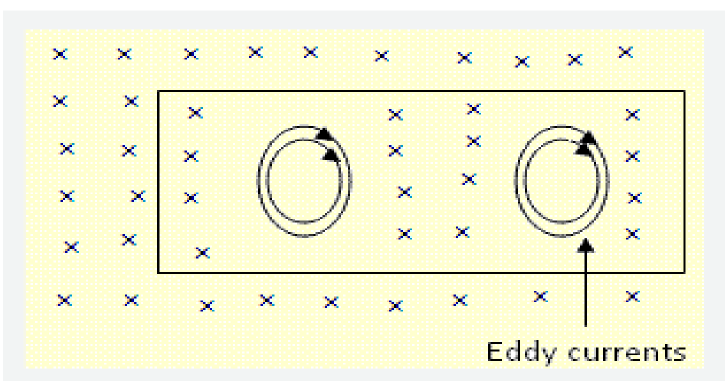

Figure 11. The Eddy current [7]

3.3 Magnetic levitation technology and some basic principles

Magnetic levitation occurs when, due to an inhomogeneous magnetic field, the force operating on an object is strong enough to balance the body's weight resulting from the effect of the Earth's gravity. The effect is not noticeable, however, in a homogeneous magnetic field; the atoms also need to be within a magnetic field gradient. If the product of the field strength and the field gradient is large enough, then the force exerted on the atoms is sufficient to counteract the effects of gravity. That is why we can consider it as a highly advanced technology. Though, magnetic levitation has various uses. The common point of all these applications is the lack of contact and thus no wear and friction, which increases the efficiency, reduces the maintenance costs and increases the useful life of the system.

It is such amazing technology, but unfortunately limited by some strictly defined rules, highly recommended to be followed. For the maglev trains to operate in high speeds, it is needed to perform some given functions which are levitation, propulsion and lateral guidance as they are shown in the Fig. 12. [9]

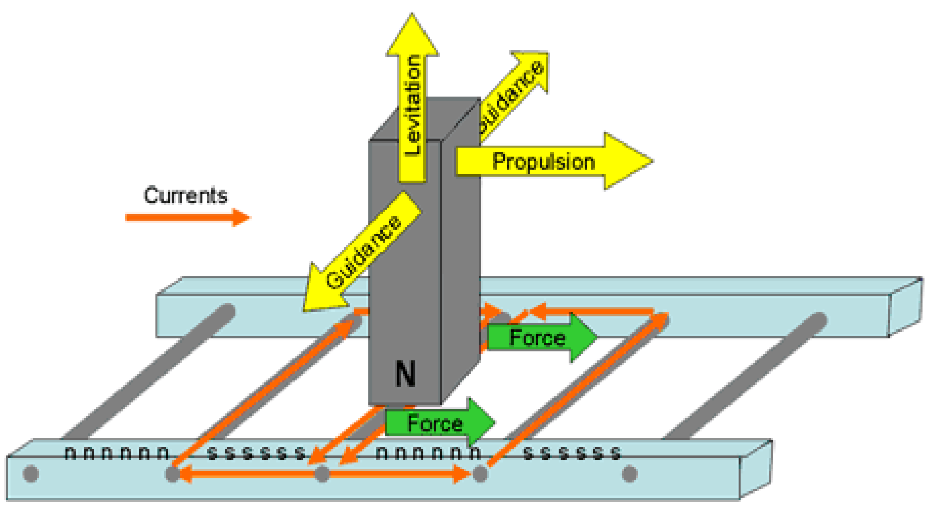

Figure 12. Basic principle of maglev trains [8]

According to the technique used for levitation, we can mention two types of maglev trains:

- Electromagnetic Suspension – Attractive
- Electrodynamic Suspension – Repulsive

These techniques are also shown in the Fig. 13.

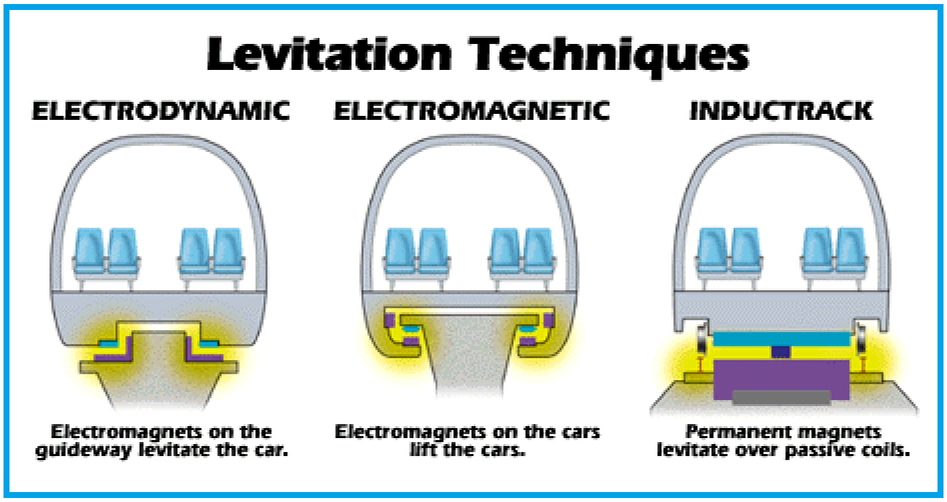

Figure 13. Levitation techniques [9]

The first type mentioned above, the Electromagnetic Suspension (EMS) uses electromagnets to levitate the train. In the case of the EMS – Attractive system, the electromagnets which cause the levitation are located on the top side of a casing that extends below and then curves back up to the rail that is in the center of the track. The rail is of a ferromagnetic material and has the shape of an inverted T. When the current goes through it, and the electromagnet is switched on, there is an attraction and the levitation electromagnets, which are below the rail raise up to meet the rail and this results in the levitation of the train.

For this system the principle of propulsion is as following. The linear electric motor (LIM) is a mechanism used to convert the electrical energy directly into linear motion without any rotary components. Instead of producing rotary torque from a cylindrical machine, it produces linear force from a flat one. The thrusts of the motor vary just a few thousands of Newtons, depending mainly on the size. The speeds vary from zero to some meters per second and are determined by design and supply frequency. [9]

The lateral guidance principle of the EMS system is further explained. The levitation magnets and the rail have the U shape. Both openings of U are facing each other. This kind of configuration ensures that when a levitation force is exerted, a lateral guidance force occurs as well. So, in such case, if the electromagnets start to shift laterally from the center of the rail, the lateral guidance force is exerted in proportion to the extent of the shift, bringing the electromagnet back into the alignment. A detailed information about this technique is shown in the Fig. 14.

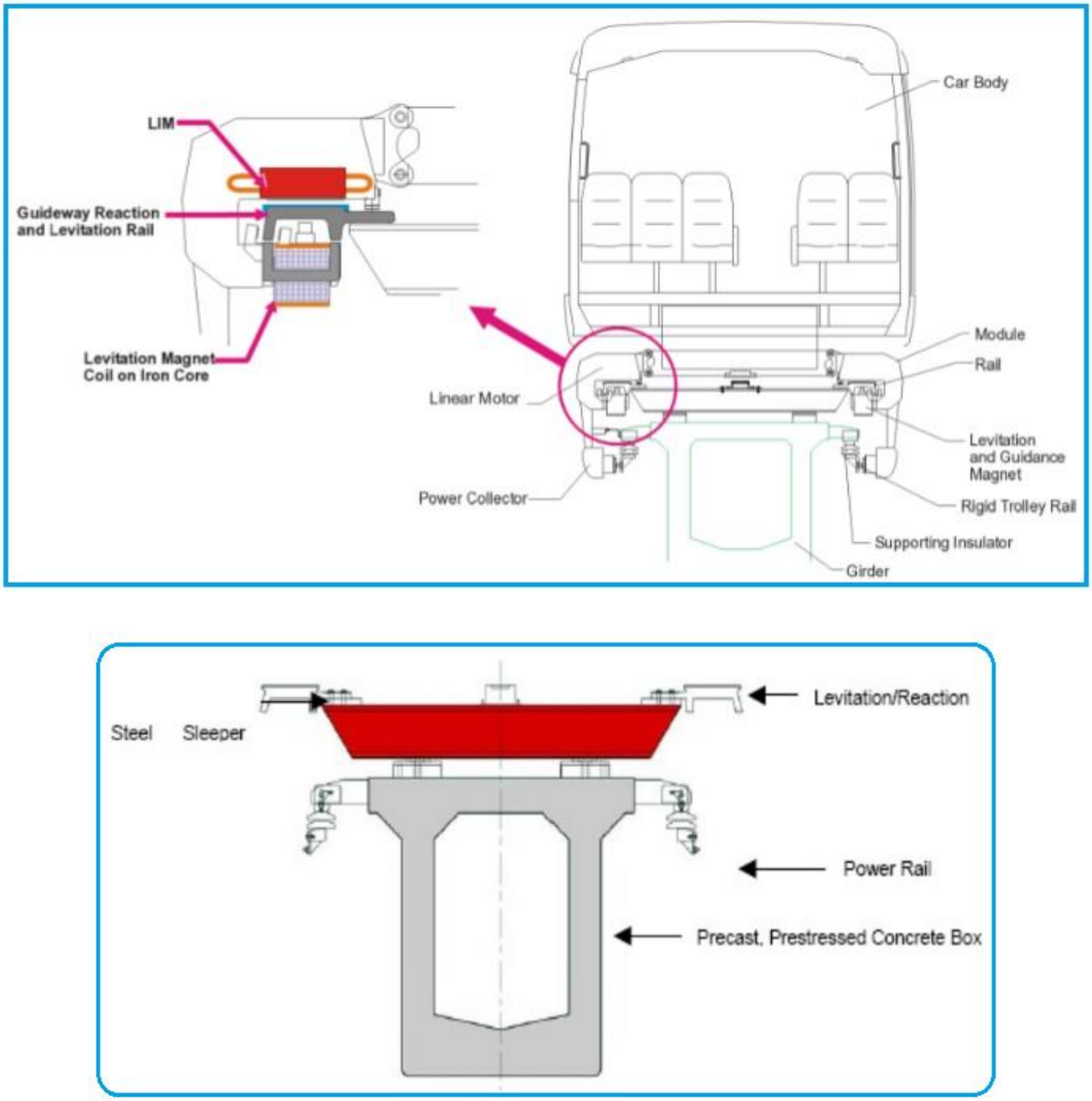

Figure 14. The EMS levitation system [9]

The second type, the Electrodynamic Suspension, uses superconductors for levitation, propulsion and lateral guidance. Superconductivity occurs in certain materials at very low temperatures. When changing to a superconductive material, its electrical resistance is approximately zero. This kind of materials are characterized by a phenomenon, the so called the Miessner effect, which is the injection of the weak magnetic field from the interior of the superconductor as it is changing to the superconducting state. The magnetic levitation in the EDS system is that the passing of the superconducting magnets near the group of eight levitation coils on the side of the tract induces a current in the coils and creates a magnetic field. This pushes the train upward so that it can levitate about 10cm above the track. The train cannot levitate at speeds lower than 50mph, so it is equipped with retractable wheels. This principle of Maglev is shown in the following figure. [9]

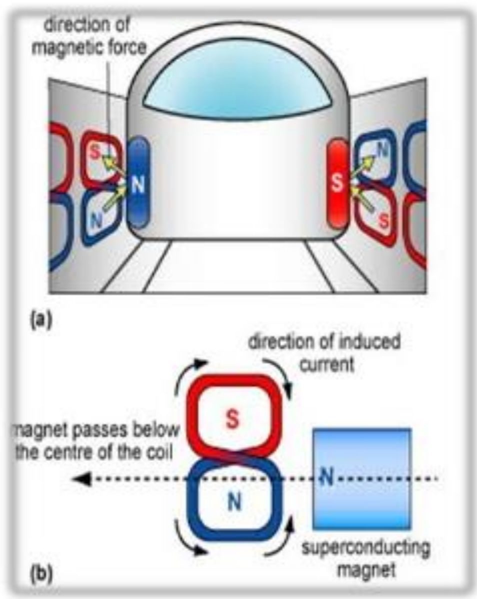

Figure 15. The principle of levitation [9]

The propulsion coils located on the sidewalls on the both sides of the guide way are energized by a three-phase alternating current from a substation, creating in this way a shifting magnetic field on the guide way. The on-board superconducting magnets are attracted and pushed by the shifting field, propelling the Maglev train. Braking is accomplished by sending an alternating current in the reverse direction so that it is slowed by attractive and repulsive forces. The principle of lateral guidance is set up in such a way so that when one side of the train nears one of the sides of the guide way, the superconducting magnet on the train induces a repulsive force from the levitation coils on the side closer to the train and an attractive force from the coils on the farther side. This will ensure that the train will stay in the center. The Fig. 16 and Fig. 17 show the relevant principle of propulsion and lateral guidance. [9]

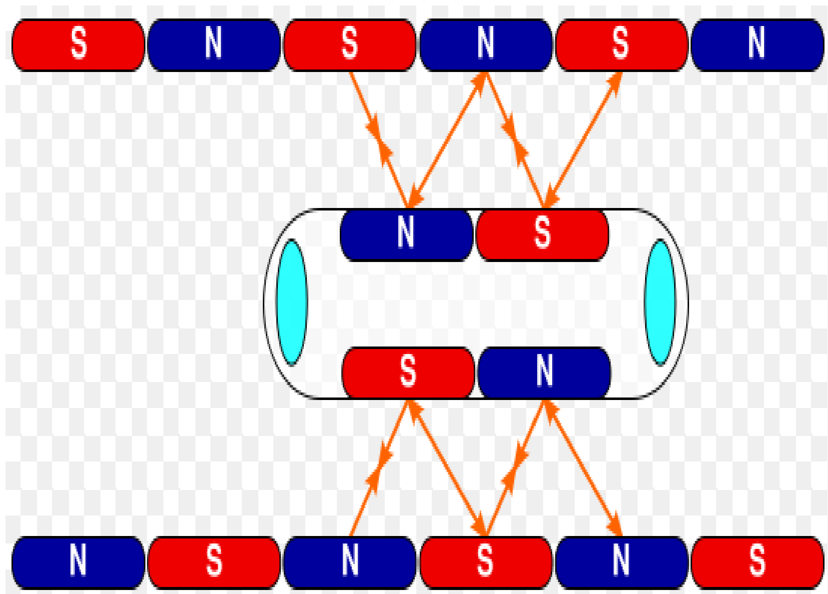

Figure 16. The principle of propulsion [9]

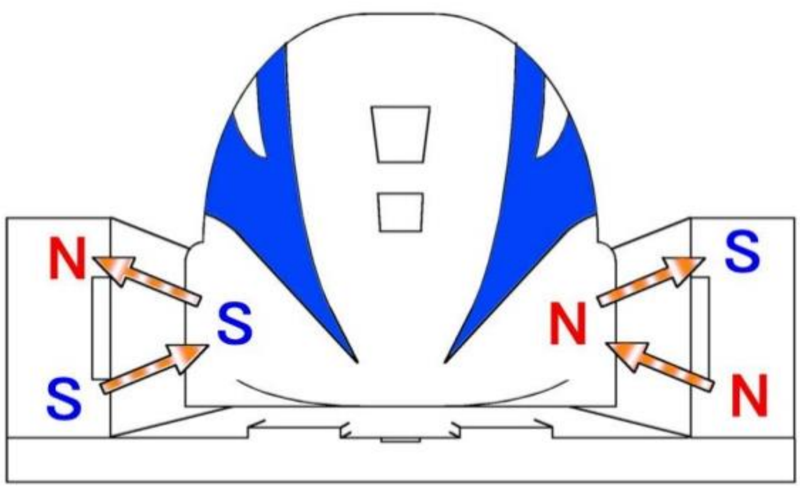

Figure 17. The principle of lateral guidance [9]

Each of these two types is characterized from pros and cons. The EMS system has a big advantage comparing to EDS system because the magnetic fields inside and outside the train are very small. This technology can achieve a speed up to 500kmh^{-1} and no wheels or secondary propulsion system is needed. But is has a big disadvantage because the separation between the train and the guideway must be constantly monitored and corrected by a computer to avoid collision and this correction by outside systems can cause vibration in the system. [9]

The second type have onboard magnets and large margin between the rail and the train, so it enables higher traveling speeds comparing to the previous type, approximately 581kmh^{-1} and the system is cooled with inexpensive liquid nitrogen. The strong magnetic field onboard will make inaccessible to passengers the magnetic data storage such as hard drives, credit cards, etc. Important is also, that the train must be embedded with wheels while travelling at low speeds. [9]

3.4 The most important applications

There are already many countries that are attracted from maglev systems because this technology can be used as an efficient one in the various industries. Many project have been proposed worldwide.

Firstly, one of the major applications of magnetic levitation was in supporting airplane models in wind tunnels. Researchers have come out with the result that mechanical structures sometimes interfere with airflow enough to produce more drag than the drag force on the model. The early beginning of this technology can be said that was the solution developed by Gene Covert and his MIT colleagues in the 1950s.

Another method to achieve full levitation is to move the magnet in the presence of an electrical conductor, thereby, inducing eddy currents in the conductor and associated repulsive forces on the magnet. This was the basis of the electrodynamic approach to maglev trains proposed by James Powell and Gordon Danby in the 1960s. According to their idea in paper, this project was further developed by Japan National Railway. Strong superconducting electromagnets on cars induce eddy currents in the conducting track that produces levitation, once the cars reach sufficient speed. Levitation via induction and eddy current repulsion can also be achieved with AC fields. One important industrial application of levitation via induction and AC fields is levitation melting, which allows the melting and mixing of very reactive metals without the need for a crucible. [10]

In 1983 was given the patent for a “levitation device” that consisted of a small spinning magnet floating above a large base magnet, which was later on developed into a successful commercial product called the Levitron.

The Levitron was based in a similar principle as the rotor of the electric meter, the spinning magnet of the Levitron was pushed upward by the repulsion forces between like poles. But it floated fully contact-free, therefore it was not a static magnet, it was spinning. At first it was a big invention but later experiments showed that the stability of the Levitron is a bit more complicated. A previous model demonstrated the levitation of highly diamagnetic graphite and bismuth, and after the development of high-field superconducting electromagnets, levitation of even much weaker diamagnets like water, wood, and plastic was accomplished. Superconductors are much more diamagnetic than graphite and bismuth. They are called as superdiamagnets. [10]

The term Maglev, in general, is related with the high-speed maglev trains technology. The idea of such a train that is magnetically levitated by a feedback-controlled attractive force was evolved into the Transrapid system used in the Shanghai maglev train. A future project is that the Japan National Railway commits to construct of a roughly 300km high-speed maglev line between Tokyo and Nagoya by about 2025.

But except this, the principle of upward magnetic forces balancing the pervasive downward force of gravity, has already found many other important applications in science and technology. Maglev technology today is widely used, to be mentioned here is in medicine, it helps to circulate blood in human chests and much more, measures fine dimensions with subatomic resolution, enhances wind-tunnel and plasma research, melts and mixes reactive high-temperature metals, cools our laptops, helps in invention of integrated circuits with multimillion-dollar photolithography systems, etc. [10]

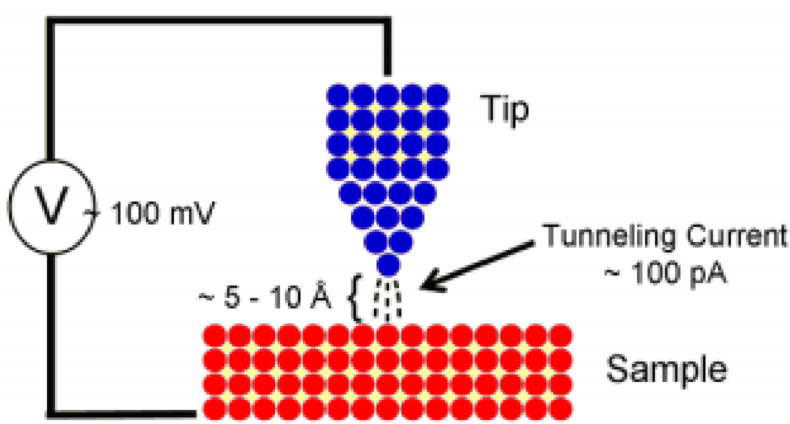

Figure 18. A schematic of STM Microscope setup [10]

The future of maglev remains very bright. Fighting the forces of gravity and friction is one of the things that magnets do best. [10]

Some of the main branches where we can find applications of magnetic levitation technology are listed below:

- Transportation engineering (magnetically levitated trains, flying cars, etc.)
- Environmental engineering (small and huge wind turbines, etc.)
- Aerospace engineering (spacecraft, rocket, etc.)
- Military weapons engineering (rocket, gun, etc.)
- Nuclear engineering (the centrifuge of nuclear reactor)
- Civil engineering (building facilities and air conditioning systems, etc.)
- Biomedical engineering (heart pump, etc.)
- Chemical engineering (analyzing foods and beverages, etc.)
- Electrical engineering (magnet, etc.)
- Architectural engineering and interior design engineering
- Automotive engineering (car, etc.)
- Advertising engineering

4. Chapter: Types of planar actuators

4.1 General background

As accurate positioning is required in many industrial processes, such as semiconductor lithography scanners, pick-and-place machines, etc., control engineering is widely used nowadays. The construction of electromechanical machines is also part of this industrial branch, since they are mainly designed and then set to function, where the control issues are also solved. The most common one are the machines which have a single degree-of- freedom, even though more complex samples are built in the recent years, such is for example a six degree of freedom planar actuator. As the number of freedom-degrees rises, new concepts are found and other problems are needed to be solved such as: directionality, linearization by feedback, controllability and the complexity of the actuator starts to influence the design process. Usually, a multiple-degree-of-freedom system (DOF) is constructed by using single-degree of freedom linear and rotary drives. But as the science is going further and further, nowadays is possible to combine multiple-degrees-of-freedom drives in one actuator. In recent years, as it was mentioned above, planar actuators are being used widely in the semiconductor industry, which is continually leading to smaller and smaller devices, able to fulfill multiple functions for a cheaper price. The features on the chips are strongly dependent on the wavelength of the light used during lithography, which means the smaller wavelength, the higher features on the chip. Known as the next-generation lithography technology, this technology uses an extreme-ultraviolet light source during the lithographical steps. In order to avoid effects, such as contamination of optical elements and absorption of the extreme-ultraviolet light by the air, the silicon wafers are exposed in a high-vacuum environment. To achieve an accurate position of the wafers, magnetically levitated planar drives are used. There exist two ways to construct a planar actuator. It has either moving coils and stationary magnets, or moving magnets and stationary coils. The first type is only described in the next section of this chapter. The second will be described in details not only in this chapter but also in the following ones, as the aim of this thesis to construct a planar actuator with stationary coils and moving magnets. But, the reality of magnetic bearing used for rotary machine shafts and magnetically levitated trains is far from these simple devices. In Maglev trains there is no physical decoupling of the levitation and the propulsion functions, as are the same coils and magnets that fulfill these functions. So, we can consider these planar actuators, a special class of multi-phase synchronous permanent-magnets motors. The following two sections are devoted to two basic types of planar actuators: the moving-coil planar actuator and the moving-magnet planar actuator. In the Fig. 19 is shown a very simple structure of a planar actuator. [11]

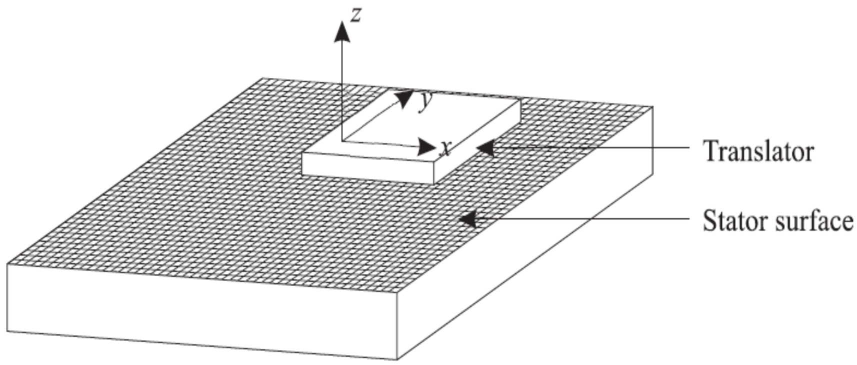

Figure 19. The planar actuator [12]

4.2 Moving-coils planar actuators

One type of planar actuators consists of moving coils and stationary magnets. The main advantage of such actuators is that they use less coils and their amplifiers, because the stroke force in the xy-plane can be easily increased by adding a few more magnets in the magnet array. Moreover, the simple design of these actuators allows control of the torque on the translator part by using different transformations. But these actuators have also some disadvantages, where the most important one is that a cable is used to connect translator and stator, as the coils require power and cooling. This type of actuator is shown in the following Fig. 20. [11]

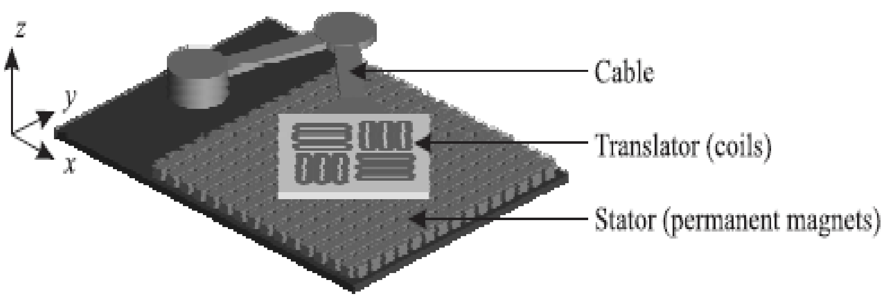

Figure 20. The moving-coils planar actuator [11]

There exists a variety of topologies related to the moving-coils planar actuators. The most known ones are the square coil topology shown in the Fig. 21, using the so called Halbach magnetic array, the Herringbone Pattern Planar Actuator (HPPA) shown in the Fig. 22, using rectangular coils, etc.

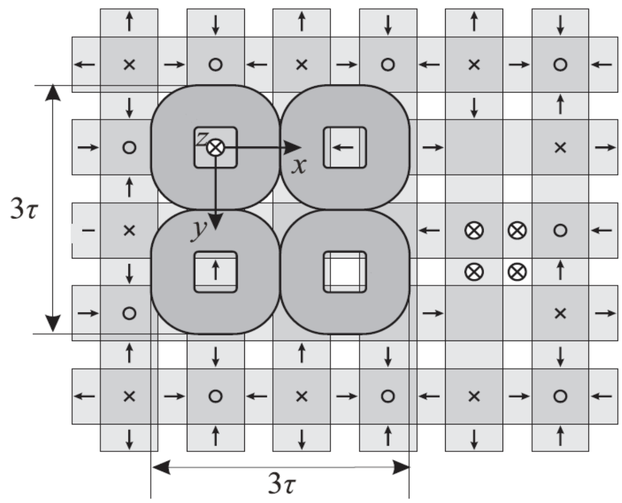

Figure 21. The square coil topology using Halbach magnet array [11]

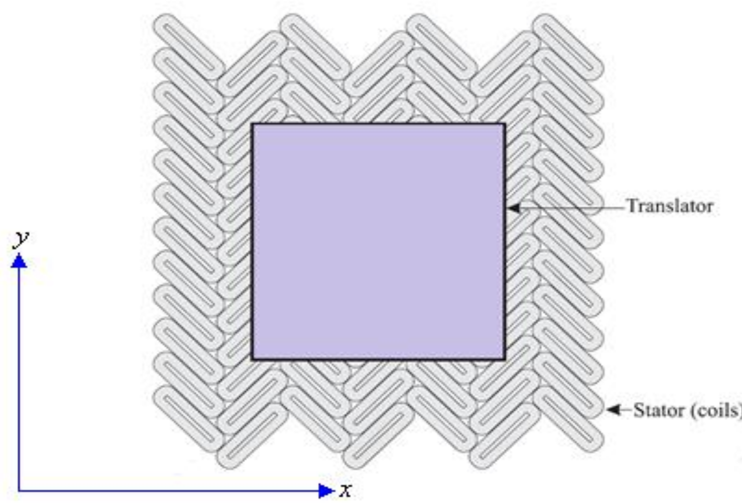

Figure 22. The Herringbone Pattern Planar Actuator (HPPA) [11]

4.3 Moving-magnets planar actuators

The second type of planar actuators consists of moving magnets and stationary coils. Exactly this is the aim of this thesis, to construct such type of actuator. In contrary with the previous type of actuator, this one don't require a cable for connecting the translator with the stator part, and this is a really big advantage from the design point of view. The coils, which require power and cooling, are now part of the stator that leads to another advantage, the reduction of the amount of disturbances to the translator. But, the torque decoupling as a function of position is more complex than in the moving-coils planar actuators. In the following figure is shown an example of this type of planar actuators. [11]

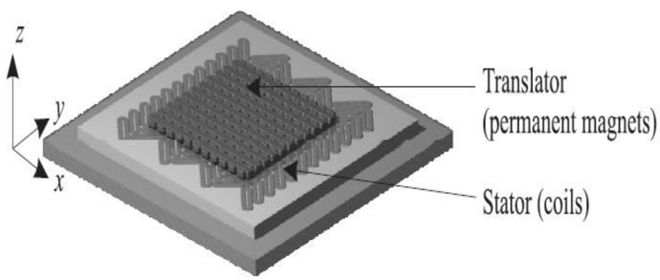

Figure 23. Moving-magnets planar actuator [11]

There exist different topologies also for this type of planar actuator. A much known structure is shown in the Fig. 24, a moving-magnets actuator with two layers of stator coils and two types of translators with different magnet arrays.

Another example is the moving-magnet planar motor shown in the Fig. 25.

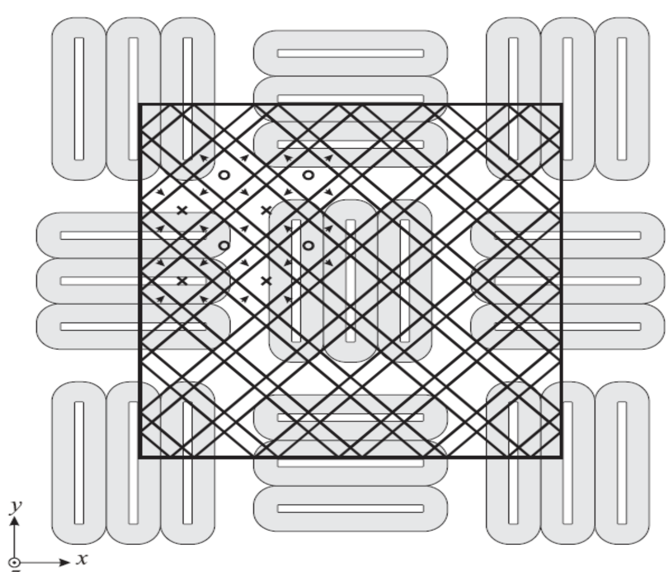

Figure 24. Planar motor with moving magnets [12]

5. Chapter: Design of the device

A block diagram of the system, which is designed for the purpose of this thesis, including its main elements is shown in the following Fig. 25.

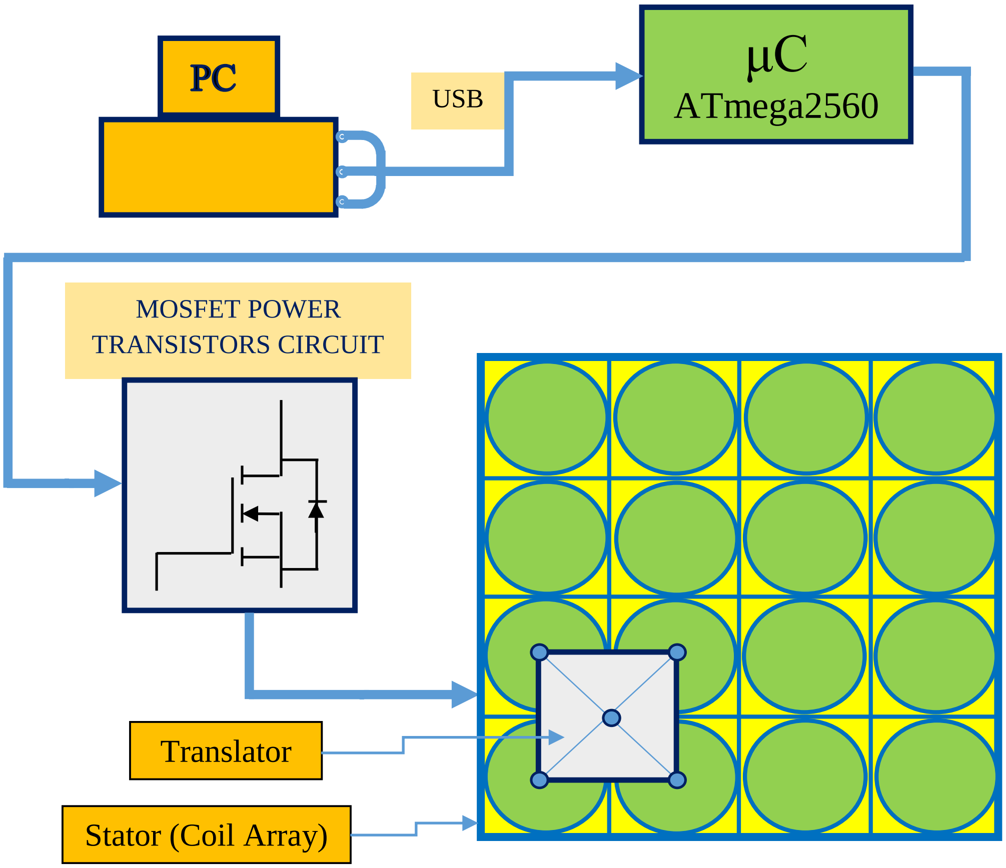

Figure 25. Block diagram of the planar actuator with moving magnets

The major objective is the design and construction of a contactless, magnetically levitated planar actuator, with moving magnets. The translator of these planar actuators is levitated above the platform with no support other than the magnetic field created from the stator part. As a translator is used a uniform shaped object with the center of mass coincident with the center of geometry. This is embedded with four stabilizing permanent magnets on every corner, so that it can provide sufficient control force against the lateral forces and with one levitating permanent magnet on the bottom of the carrier to counteract the weight of the carrier. The stator part is represented by 4 blocks with 4 coils each, in total 16 identical coils and a microcontroller board for positioning control of the translator.

The aim of the stator design is the arrangement of the cylindrical solenoids and their floating currents in such a way, so together would form a uniform magnetic field over a planar surface slightly above the coil array.

5.1 The stator part of the planar actuator

This section deals with detailed information about the stator part of the device. For this project, the stator consists of 16 partially identical coils, which are winded by hand. Each is about 30mm in height, with an inner diameter of 10mm, an outer diameter of 15mm, and have 300 windings each. These are arranged together in order to form 4 blocks with 4 coils each, so a 4x4 array. The type of the wire used for the coils is made from copper and varnished with a layer of isolator in order to prevent short-circuit. The wire has a diameter of 0.35mm and is a product of the company known as Block.

In the stator will be included as well the controlling device, used to switch the current between the coils through PWM signals. The chosen type of microcontroller is Arduino Mega 2560. The electrical and other parameters of this device will be explained further in this thesis. As the output pin current from Arduino board can't be higher than 40mA, which mean that the magnetic field around the coils is very weak, an external circuit of power MOSFET transistors is designed. One circuit can control only one block of 4 coils, so in order to control the whole array, 4 similar circuits are constructed. The coils themselves are supplied by an external supply source, in range between 12 to 20V. An important part of this design is also continuous cooling conditions for the coils. This issue was solved by producing coils with wider internal diameter and also by the limitation of the current which flows through each of the coils, in order to avoid overheating.

5.2 The translator part of the planar actuator

The design of the translator part of this device is much easier than that of the platform. As mentioned above, this is the type of planar actuator with moving magnets, so it is clear that the translator will consist of several magnets. But the problem is not that easy either. Firstly, stabilization of the translator is required. This can be done by the construction of such a uniform shaped object with the center of mass coincident with the center of geometry. Important is the issue that in numerical analysis the levitation distance between the magnet to be levitated and the cylindrical solenoid underneath is strongly related with the magnetic flux in between. If such a distance is very small, then the magnetic flux approaches a constant value. The aim of the stator design is the arrangement of the cylindrical solenoids and their floating currents in such a way, so together would form a uniform magnetic field over a planar surface slightly above the coil array. Therefore, the structure of the translator which uses a permanent magnets becomes the most optimal choice to meet the purposes and the goals of this thesis.

In order to make the carrier lightweight and to avoid magnetization with the stator part, for construction of the translator it is recommended to use such kind of material, for example aluminum or similar. The goal is to build such a carrier which will meet the requirements of obtaining a planar two-dimensional positioning. From the experienced gained due to different tests during the construction of this device, I came to the decision that in the positioning system, the existence of the levitating force due to repelling between the translator and stator usually causes destabilization of the carrier in the lateral direction. In order to avoid this, the translator is embedded with four stabilizing permanent magnets on every corner so that it can provide sufficient control force against the lateral forces and with one levitating permanent magnet on the bottom of the carrier to counteract the weight of the carrier.

To be able to achieve a high-precision positioning performance, it is needed first of all the control and the altitude of the carrier properly. To fulfil this purpose, we must follow some simple steps, as follows:

Assumptions:

A. Each of the magnet used in the translator part is considered a single dipole carrying the same magnetic dipole moment. This dipole is located at the center the magnet.

B. The array of cylindrical solenoids and the adjustment of their floating currents is constructed in a way that they form a plane above the top face of the array with uniform magnetic field.

C. Each of the permanent magnets on the corners of the carrier are far separated from each other so that the influence in between can be neglected.

6. Chapter: Stabilization and control of the translator

6.1 Methods applied for stabilization

This chapter is devoted to the development of analytical tools for predicting electromagnetic field properties. This is related with the stabilization of the translator while moving slightly above the stator part. One solution is related with connection between the coils inside one single block which consists of four coil. Each two of these coils are connected in series with each other, and in this couple one coil attracts the translator and the other coil repeals it. The same function is applied on the second couple of the same block. Furthermore, under the stator part are placed several magnets. This repulsive force is added to the repulsive and attractive forces generated from the coils. The schematic diagram for one block of four coils is shown in the following Fig. 26. This solution is proved to be effective, but it is not applied in this thesis, for the only reason that the designed supply circuit consisting of MOSFET transistors, further explained in this thesis, supplies at the same time all the four coil of a single block, and the coils are connected in series with each other.

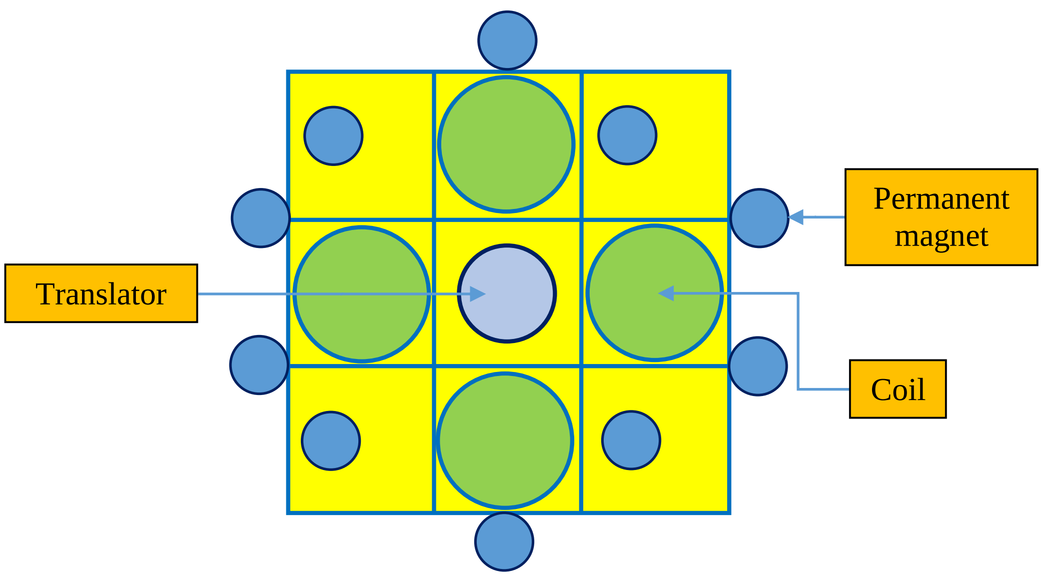

Figure 26. First method for stabilizing the translator

Another method of stabilization is related to control from Arduino board and the design of translator, as it is shown in the Fig. 27. The translator consists of five permanent magnets. Four of them are placed on the corners, arranged so that the center of each magnet will meet the center of the relevant coil. The coils are controlled through PWM signals from the controller board Arduino Mega 2560. Each PWM signal is characterized from a different duty cycle.

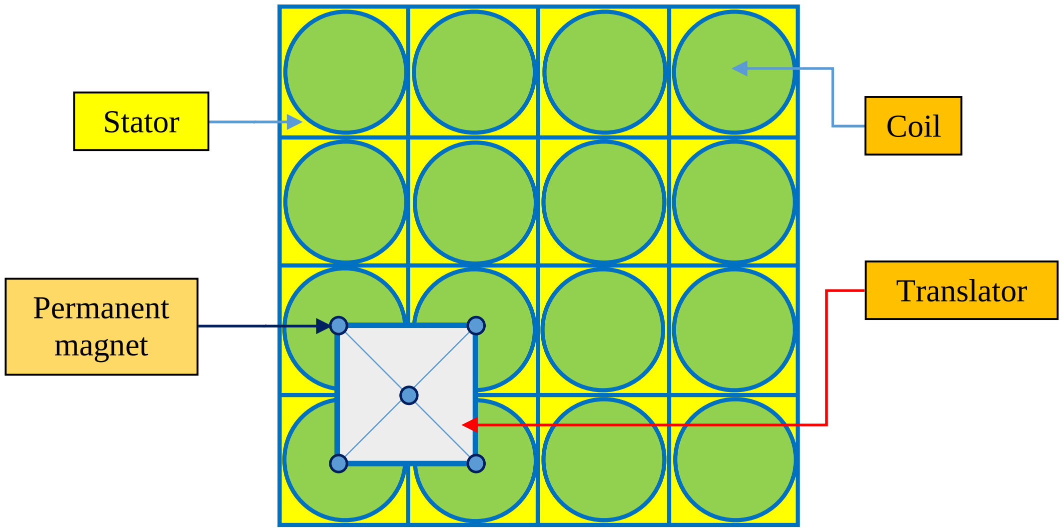

Figure 27. Second method for stabilizing the translator

6.2 The supply and control of the device

The supply of the coils positioned in the stator is done from an external power supply connected to the supply pins of the circuits with the MOSFET power transistors. As the pin output current is approx. 40mA, this is not enough to drive the coils. Consequently, for full control of floating current of the coils in the stator, I needed four circuits using MOSFET power transistors. This works like a bridge between the external supply source, the Arduino board and the stator. From the circuit shown in the Fig. 28, it is visible that the main element is the MOSFET transistor. Not less important element is the optocoupler which is used for galvanic division between two parts of the circuit, the one where the pin from the board is connected and that which includes the coil. The snubber diode is used for protection, in order to block the voltage drop, while the current is being switched between the coils.

Further details about the electrical characteristics concerning to this circuit and to relevant coil of the stator are given in Tab. 1.

Table 1: Electrical parameters of the circuit with MOSFET transistors

Parameter	Value			Unit
	min	typical	max	
Supply voltage	10	12	20	V
Temperature range	-40	-	85	°C
Coil current	-	0.5	-	A
Magnetic field around coils	-	62	-	µT
Coil resistance	-	4.9	-	Ω
Frequency	-	980	-	Hz

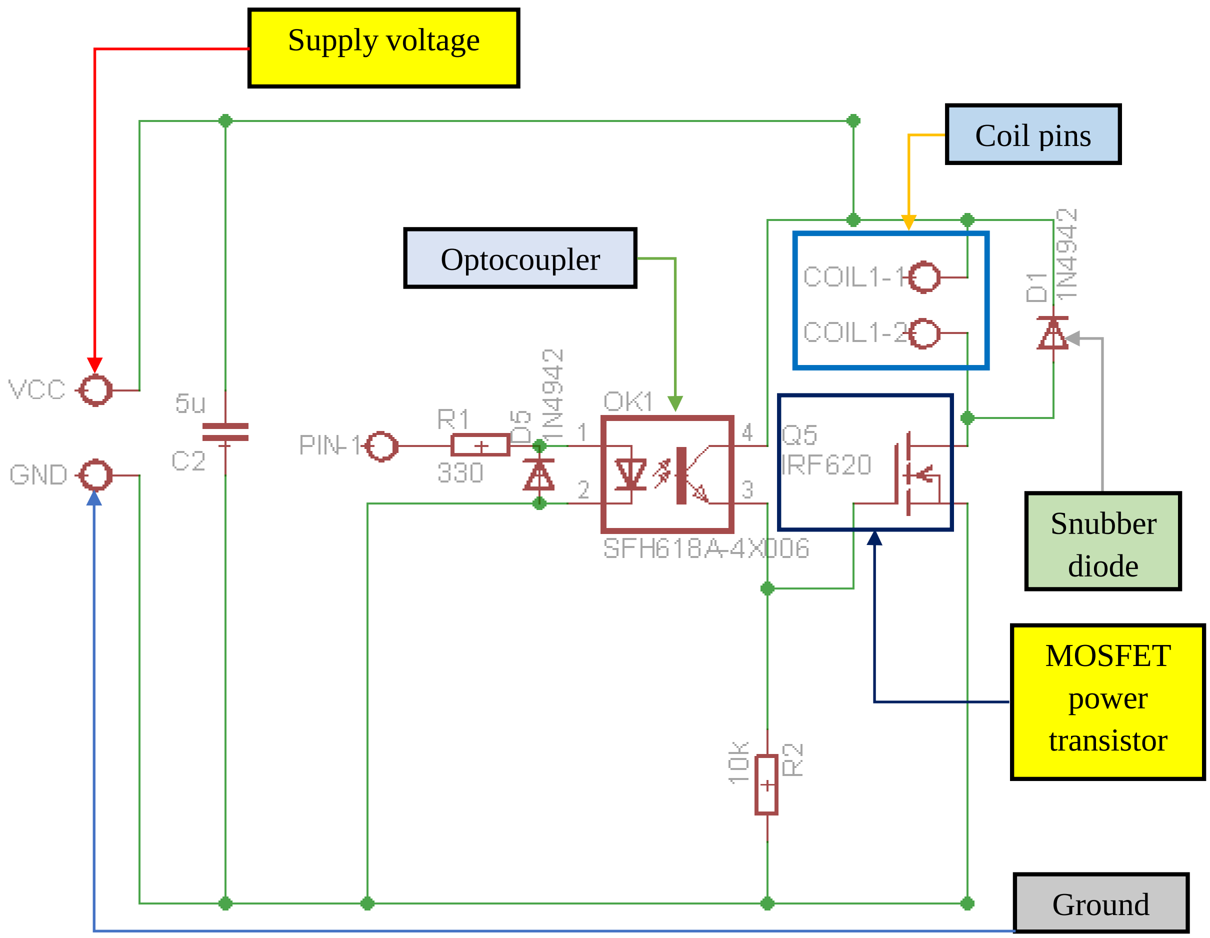

Figure 28. The circuit used to supply and control one single coil

As it was mentioned above, positioning control of the carrier is done through the microcontroller by the PWM signals. Arduino Mega 2560 meets the technical requirements of this thesis and which it doesn't affect the total cost of the final device, it is programmed using the assembler programming language. The microcontroller itself can be supplied by a computer via a USB cable or power it with through an external supply, or non-USB power which can be represented by an AC-to-DC adapter or battery.

Arduino Mega 2560

The Arduino Mega 2560 is a microcontroller board based on the ATMega2560. This device consist of 54 input/output pins, out of which 15 can be used as PWM outputs, 16 other analog inputs, 4 hardware serial port UARTs, a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header and reset button to return the device into its initial condition. The Arduino Mega 2560 is very simply to use and as well very user-friendly. It contains everything needed to support the microcontroller. You can use as a supply one of the two possibilities that this device offers, either connect it to a computer via a USB cable or power it with through an external supply, or non-USB power which can be represented by an AC-to-DC adapter or battery. [13]

<u>General overview</u>

As mentioned above, the Arduino Mega can be powered via the USB connection or with an external power supply, whereas the power source is selected automatically. The board's power jack is used to connect a 2.1mm center-positive plug in the case that an adapter is chosen to supply the device. The leads coming out from a battery can be inserted in the Gnd and Vin pin headers of the POWER connector. The operation voltage range of the board through an external supply is 6V to 20V. The power pins are as follows:

- VIN. The input voltage to the Arduino board when it's using an external power source (as opposed to 5V from the USB connection or other regulated power source). You can supply voltage through this pin, or, if supplying voltage via the power jack, access it through this pin.
- 5V. This pin outputs a regulated 5V from the regulator on the board. The board can be supplied with power either from the DC power jack (7 - 12V), the USB connector (5V), or

the VIN pin of the board (7-12V). Supplying voltage via the 5V or 3.3V pins bypasses the regulator, and can damage your board.

- 3V3. A 3.3V supply generated by the on-board regulator. Maximum current draw is 50mA.
- GND. Ground pins.
- IOREF. This pin on the Arduino board provides the voltage reference with which the microcontroller operates. A properly configured shield can read the IOREF pin voltage and select the appropriate power source or enable voltage translators on the outputs for working with the 5V or 3.3V.

If the Arduino Mega is supplied with less than 7V, which is not recommended by the producer, however, the only thing that might occur is that the 5V pin may supply less than five volts and the board may be unstable. On the other hand, if using more than 12V, the voltage regulator may overheat and damage the board. The recommended range is 7 to 12V. [13]

Memory

The ATmega2560 has 256KB of flash memory for storing code, of which 8KB is used for the bootloader, 8KB of SRAM and 4KB of EEPROM. This can be read and written from the EEPROM library.

Inputs and outputs

All of the 54 digital pins on the Mega can be used as an input or output. The recommended voltage applied in to this pins is 5V. Each pin can provide or receive a maximum value of 40mA and has an internal pull-up resistor (disconnected by default) of 20-50Ω. In addition, some pins have specialized functions:

- Serial: 0 (RX) and 1 (TX); Serial 1: 19 (RX) and 18 (TX); Serial 2: 17 (RX) and 16 (TX); Serial 3: 15 (RX) and 14 (TX). Used to receive (RX) and transmit (TX) TTL serial data.
- External Interrupts: 2 (interrupt 0), 3 (interrupt 1), 18 (interrupt 5), 19 (interrupt 4), 20 (interrupt 3), and 21 (interrupt 2). These pins can be configured to trigger an interrupt on a low value, a rising or falling edge, or a change in value.

- PWM: 2 to 13 and 44 to 46. Provide 8-bit PWM output with the usage of analogWrite() function.
- SPI: 50 (MISO), 51 (MOSI), 52 (SCK), 53 (SS). These pins support SPI communication using the SPI Library. The SPI pins are also broken out on the ICSP header.
- LED: 13. There is a built-in LED connected to digital pin 13. When the pin is HIGH value, the LED is on, when the pin is LOW, it's off.

There are a couple of other pins on the board:

- AREF. Reference voltage for the analog inputs. Used with analogReference().
- Reset. Bring this line LOW to reset the microcontroller. Typically used to add a reset button to shields which block the one on the board.

The board Mega 2560 has also 16 other analog inputs, whereas each can provide 10 bits of resolution (i.e. approx. 1024 different values). By default they measure in a range from ground to 5V, though is it possible to change the upper end of their range using the AREF pin and analogReference() function.

Communication

All of the 54 digital input/output pins of the Arduino Mega 2560 has a number of facilities for communicating with a computer, with another Arduino, or other microcontrollers. The ATmega2560 provides four hardware UARTs for TTL (5V) serial communication. An ATmega16U2 provides a virtual com port to software on the computer. Generally the computers running on Windows will need an .inf format file, but OSX and Linux machines can recognize the board as a COM port automatically. The Arduino software includes a serial monitor which allows simple textual data to be sent to and from the board. The RX and TX LEDs on the board will flash when data is being transmitted via the ATmega8U2/ATmega16U2 chip and USB connection to the computer, but not for serial communication on pins 0 and 1. [13]

A SoftwareSerial library allows for serial communication on any of the Mega2560's digital pins. The ATmega2560 also supports TWI and SPI communication. The Arduino software includes a Wire library to simplify the usage of the TWI bus. For SPI communication, use the SPI library.

Programming of the board

The Arduino Mega can be programmed with the Arduino software. The ATmega2560 on the Arduino Mega comes preburned with a bootloader that allows you to upload new code to it without the use of an external hardware programmer. It communicates using the original STK500 protocol. It is also possible to bypass the bootloader and program the microcontroller through the ICSP (In-Circuit Serial Programming) header.

Automatic Software Reset

The Arduino Mega 2560 does not require a physical press of the reset button before uploading the code to the microcontroller. The board is designed in a way that allows it to be reset by software running on a connected computer. The Data Terminal Ready (DTR) hardware flow control line of the ATmega8U2 is connected to the reset line of the ATmega2560 via a 100nF capacitor. When this line is asserted as low, the value reset line drops long enough to reset the chip. This capability is a big advantage while programing the board because it allows the user to upload the code by simply pressing the upload button in the Arduino environment. This means that the bootloader can have a shorter timeout, as the lowering of DTR can be well-coordinated with the start of the upload.

USB Overcurrent Protection

The Arduino Mega 2560 has a resettable polyfuse that protects your computer's USB ports from shorts and overcurrent. Although most computers provide their own internal protection, the fuse provides an extra layer of protection. If more than 500mA is applied to the USB port, the fuse will automatically break the connection until the short or overload is removed. The following Tab. 2 gives the basic electrical parameters of the board Arduino Mega2560.

Table 2: Electrical parameters of the board Arduino Mega 2560 [13] [15]

Parameter	Value			Unit
	min	typical	max	
Operating voltage	-	5	-	V
Input voltage (recommended)	7	-	12	V
Input voltage (limits)	6	-	20	V
DC current per I/O pin	-	40	-	mA
DC current for 3.3V pin	-	50	-	mA
Clock speed	-	16	-	MHz

Further on, Table. 3 and Table. 4 show the electrical and memory parameters of the microcontroller ATmega2560. [13]

Table 3: DC parameters of microcontroller ATmega2560 [14]

Parameter	Value			Unit
	min	typical	max	
Supply voltage	1.8	-	5.5	V
Temperature range	-40	-	85	°C
Input Leakage Current I/O Pin Low	-	-	1	µA
Input Leakage Current I/O PinHigh	-	-	1	µA
Reset Pull-up Resistor	30	-	60	kΩ
I/O Pin Pull-up Resistor	20	-	50	kΩ

Table 4: Memory parameters of ATmega2560 [13] [15]

Memory type	Value	Units
Flash memory	256	KB
SRAM	8	KB
EEPROM	4	KB

The Fig. 28. shows the float diagram of the code written in Assembler programing language to control the float of the translator above the platform.

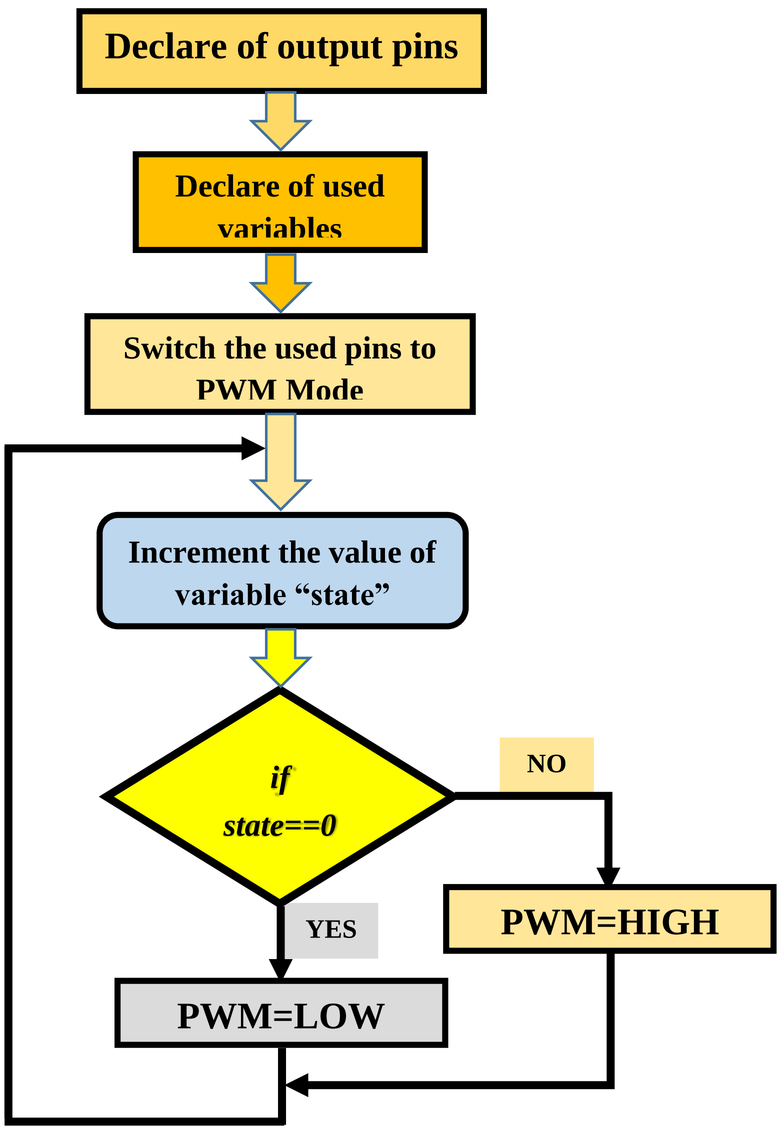

Figure 29. Float diagram of microcontroller Arduino Mega 2560

7. Chapter: Accomplished results

The designed laboratory sampled is a planar actuator with moving magnets. In the stator part, the current flowing through the coils is amplified by the designed circuit consisting of MOSFET power transistors, in order to create magnetic field strong enough to levitate the translator. The system works fine and is able to show the principle of magnetic. But, still there are some issues which need to be solved such as stabilization and control. The control is done through switching the current between relevant coils. The current is switched very fast among the coils and is controlled by PWM signals sent by the Arduino Mega 2560 controller board. Because each the PWM signals is defined to have a different duty-cycle, this is one reason which makes the system unstable. The coils which form the array of the stator platform are winded by hand, consequently the winding of the coils are not really close to each other, which changes the accuracy of the parameters of one coil from the other. The magnetic field created from the coils, slightly above the platform array will not be accurately uniform, and this influences the stability of the system. The consequences are the variations in the values of forces and torques generated by different coils, including as well the misalignments of the individual coil position.

The magnetic levitation technology is just in its beginnings and has a very bright future. From the experience gained from the design and construct of the laboratory sample described in this thesis, I would like to give some recommendations, including software and hardware, which might be valuable for the future projects concerning about Maglev:

- coils used for the stator part must have very similar parameters like internal resistance, inductivity, etc.

- minimaze the fluctuations of the magnetic field created above the coils

- well designed and stablilized translator part of the system

- precise poistioning of the coils in the platform, in order to avoid misalignments between individual coils

- very accurate timing of the PWM signals sent by the PID controller

8. Chapter: Economic representation of the device

This chapter gives some basic information about the economic calculations, concerning about producing this device in a production line of a company. The main objectives are firstly, the computation of benefits, deriving from the sale of this product and secondly, the comparison of the prices between the laboratory sample and the product fabricated in a company line. It is important to mention that the values used in these calculations, except here the prices in CZK of the circuit elements given in the Table.1, are not defined by the market, but just some created numbers.

Table 5. Costs of the circuit elements

Circuit Element	Piece	Quantity	Cost	Total
Microcontroller board ATmega2560	piece	1	1299	1299
Coil copper wire	piece	5	220	1100
Resistor 330Ω + Resistor 10kΩ	piece	32	3	96
MOSFET power transistor	piece	16	12	192
Snubber diode	piece	32	1	32
Plastic coil core	piece	32	3	96
Coil extra elements	piece	30	2	60
Total			**2875 CZK**	

Production of the laboratory sample

It is supposed that only one person will do the complete work in testing and producing this laboratory sample. The production time is about four months. The final price of the device is calculated as follows:

- the cost of the circuit elements
- the personal salary of the worker (including the health insurance)
- cost of the electrical energy [kWh]
- cost of heating in the laboratory
- cost of the replaced elements

The salary of the worker is:

- salary/hour = 150 CZK
- working hours in one day = 8 hours
- working hours in one month = 160 hours
- working hours in four months = 640 hours

*Salary = 150 * 640 = 96 000 CZK* (10)

The price of the electrical energy in four months:

- the amount of energy in kWh = 700kWh
- the price of the energy euro/kWh = 0.07 euro/kWh
- currency exchange rate euro/czk = 27

*Electrical energy = 700 * 0.07 * 27 * 4 = 5292 CZK* (11)

The price of the heating in the laboratory:

Heating = 1250 CZK (12)

Energy = Electrical energy + Heating = 5292 + 1250 = 6542 CZK (13)

During the testing process of the device, was needed to replace five resistors, two optocouplers, one MOSFET transistor and also another package of coil wire, in total 300 CZK.

The price of the laboratory sample is the sum of the units mentioned above, and it is calculated as it follows:

Cost = Circuit elements + Worker salary + Energy + Replaced Elements

= 2875 + 96000 + 6542 + 300 = 105 717 CZK (14)

The final cost of the laboratory sample is **105 717 CZK**.

Fabrication of the device in the production line

The company crew is composed by one supervisor and six workers. It is supposed that the company will produce 1000 devices/year and the production will continue for 3 years. Therefore, the final amount after 3 years of fabrication is 3000. In order to get the price for one device we need to firstly calculate:

- circuit elements
- the personal salary of the supervisor (including health insurance)
- the personal salary of the worker (including health insurance)
- price of the electrical energy
- cost of the rent of the production line
- administration costs

The personal salary of the supervisor and worker is calculated as it follows:

- supervisor salary/hour = 200 CZK
- worker salary/hour = 150 CZK
- working hours in one day = 8 hours
- working hours in one month = 160 hours
- working hours in one year = 1920 hours

Table.6 Personal salaries of the company crew

Personals				*CZK*
Description	**Nr.**	**Monthly**	**Amount/month**	**1 Year**
Supervisor	1	32 000	32 000	384 000
Worker	6	24 000	144,000	1 728 000
Total			**176 000**	**2 112 000**

The price of the electrical energy in one year:

- the amount of energy in kWh = 3000kWh
- the cost of the energy euro/kWh = 0.07 euro/kWh

- currency change euro/czk = 27

$$Electrical\ energy = 3000 * 0.07 * 27 * 12 = 68\ 040\ CZK \quad (15)$$

The cost for the rent of the production line includes:

- the amount in euro
- currency exchange rate euro/czk = 27
- number of months = 12

$$Rent = 600 * 27 * 12 = 194\ 400\ CZK \quad (16)$$

The administration costs are as follows:

- administration costs/month = 250 CZK

$$Administration\ costs = 250 * 12 = 3000\ CZK/year \quad (17)$$

The costs in one year:

$$Costs = Salaries + Electrical\ energy + Rent + Administration\ costs$$

$$= 2112000 + 68040 + 194400 + 3000 = 2\ 377\ 440\ CZK \quad (18)$$

The costs for one device we can calculate:

$$Cost\ for\ 1\ device = Costs/1000 = 2377\ CZK \quad (19)$$

Then the price for one device is:

$$Price = Circuit\ elements + Costs\ for\ 1\ device$$

$$= 2377 + 2875 = 5252\ CZK \quad (20)$$

The state taxation for each device is:

$$State\ taxation = 40\% * 5252 = 2100.8\ CZK \quad (21)$$

The final price of the device, including the taxation fee is calculated as it follows:

Final price = Price + State taxation = 5252 + 2100.8 = 7352.8 CZK (22)

The taxation cost for 3000 devices, is the calculated amount:

*Taxation total = 2100.8 * 3000 = 6 302 400 CZK* (23)

The benefits from the sale of 3000 devices are:

Benefits = Price * 3000 = 7352.8 * 3000 = 22 058 400 CZK (24)

From the above calculations, the benefits of the company deriving from the sale of the produced device have the value of **22 058 400 CZK**. The price of the laboratory sample has the value of **105 717 CZK**. The value of the device fabricated in the production line is **7352.8 CZK**. It is understandable that the laboratory sample is more expensive, influenced by these three reasons:

- ✓ Firstly, during the production of the laboratory sample, we had extra costs for the circuit elements. In the production line, these costs are avoided as the experience for producing a functional sample of the device is obtained from the testing phase.

- ✓ In the second row, the increase of the production decreases the fixed costs per unit.

- ✓ Finally, the time spent for the production of laboratory circuit is longer than the time spent for the production of the same unit in the production line.

9. Chapter: Conclusion

This master thesis is aimed to design a miniature system working on the principle of magnetic levitation, which uses four blocks consisting of 4 coils each, this means in total 16 partially identical handmade coils forming the stator part of the device and also several magnets for the translator. This type of device is called a planar actuator.

The sample designed for this thesis, has several coils forming the stationary part and an array of magnets as the translator. Important component is also the microcontroller board Arduino Mega 2560. It is programmed using the Arduino programming language (based on Wiring) and the Arduino development environment and used for positioning control of the translator. The output of each of the pins is a PWM signal with different duty-cycle among pins, which controls the current flow through the relevant coil. The arrangement of the cylindrical solenoids and their floating currents, is done in a way, so that together would form a uniform magnetic field over a planar surface above the coil array. The translator, represented by a uniform shaped object, with the center of mass coincident with the center of geometry, floats easily slightly above the platform, proving so the principle of magnetic levitation. Due to the small value of current from the output pins of microcontroller board, approx. 40mA, I designed four similar circuits consisting of MOSFET power transistors. This circuit is like a bridge between the external supply source, the output pins of microcontroller and the coil array. The functionality of the laboratory sample was verified, but as mentioned above, there are still some issues, which require a more précised solution. These are mentioned in the Chapter 7 of this thesis.

In the Chapter 8 of this master thesis is performed the economic representation of the constructed device, concluding with the comparison of the price of the device produced in the laboratory and that from a production line. The results are as follows. The price of the laboratory sample has a value of **105 717 CZK**. The price of the equipment fabricated in the production line of the company reaches a value of **7352.8 CZK**. The fixed costs of the device decrease while the number of the produced samples increases. That is the reason why during the fabrication of the device on a production line, the price is lower than in the case of the sample produced in the laboratory.

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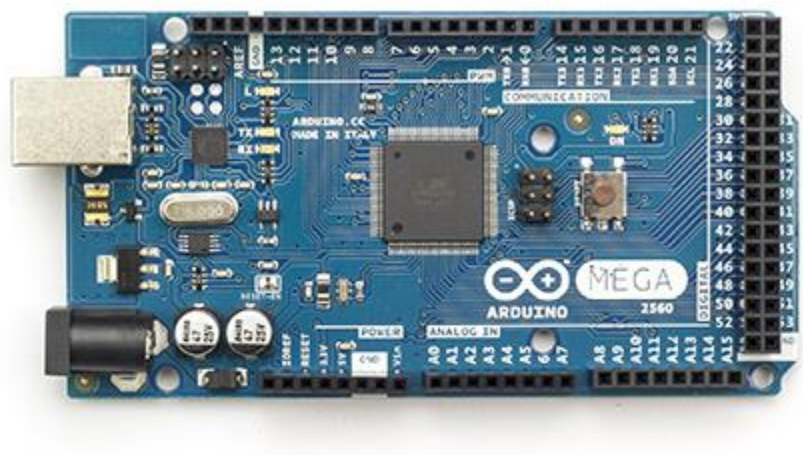
[15] Datasheet. Arduino Mega 2560. Schematic. Available online from WWW: <http://elmicro.com/files/arduino/arduino-mega2560_r3-schematic.pdf>

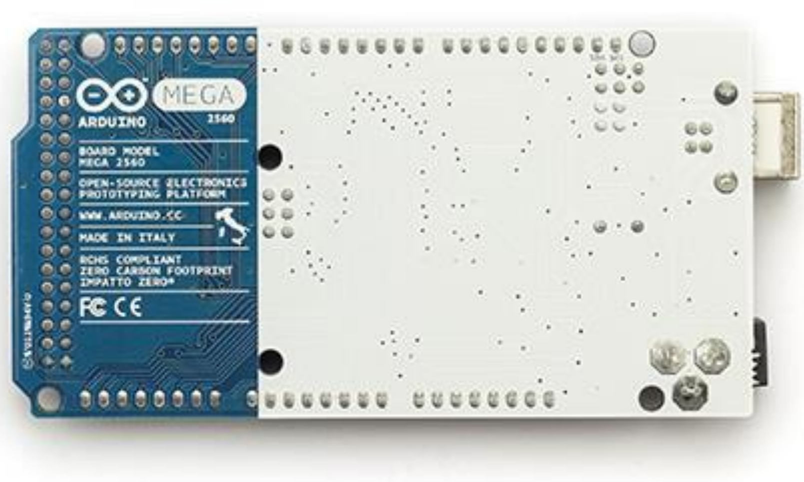
Attachments

A. Atmel ATmega2560 microcontroller board. Front view.



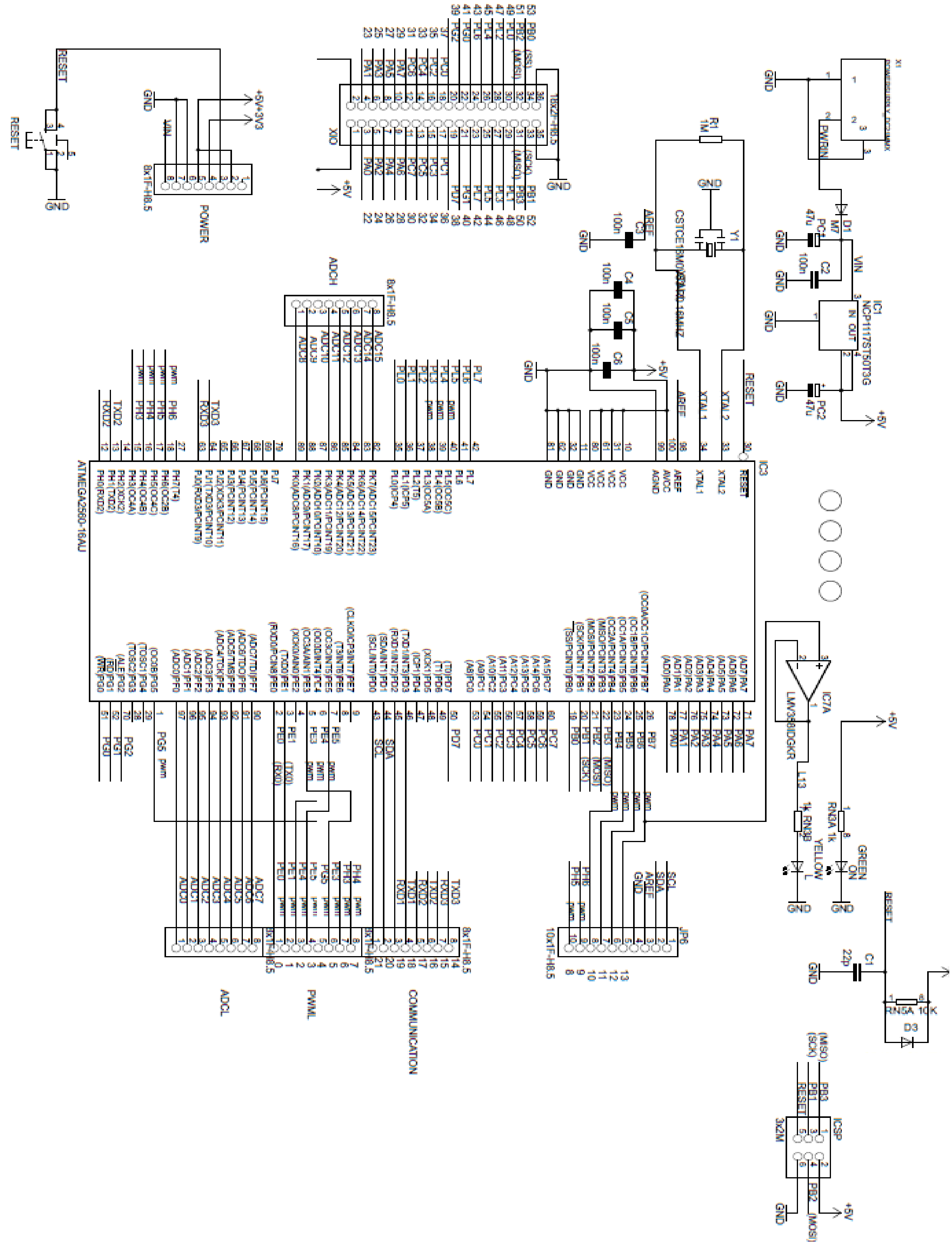
Arduino Mega 2560 R3 Front

B. Atmel ATmega2560 microcontroller board. Bottom view.

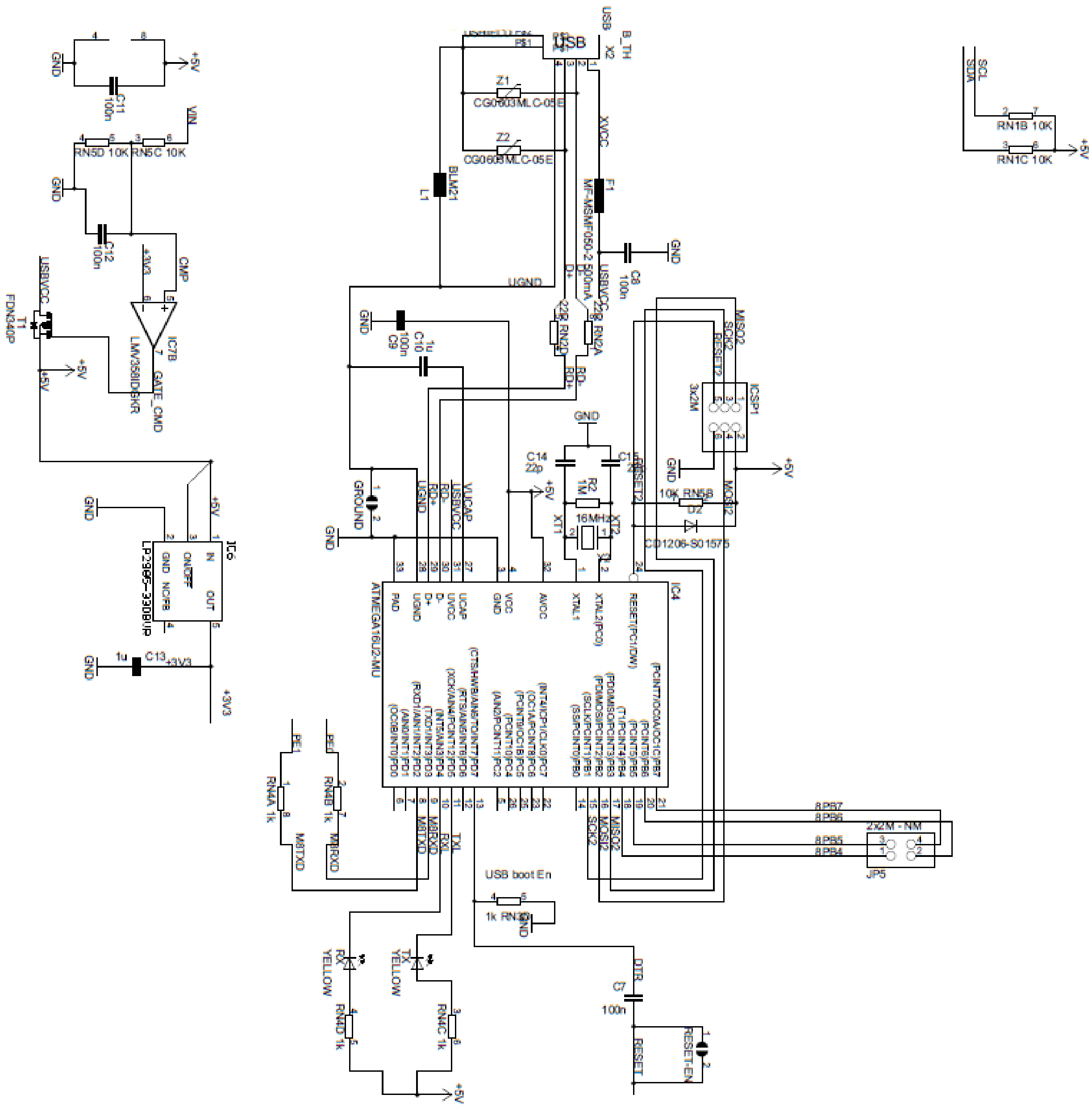


Arduino Mega2560 R3 Back

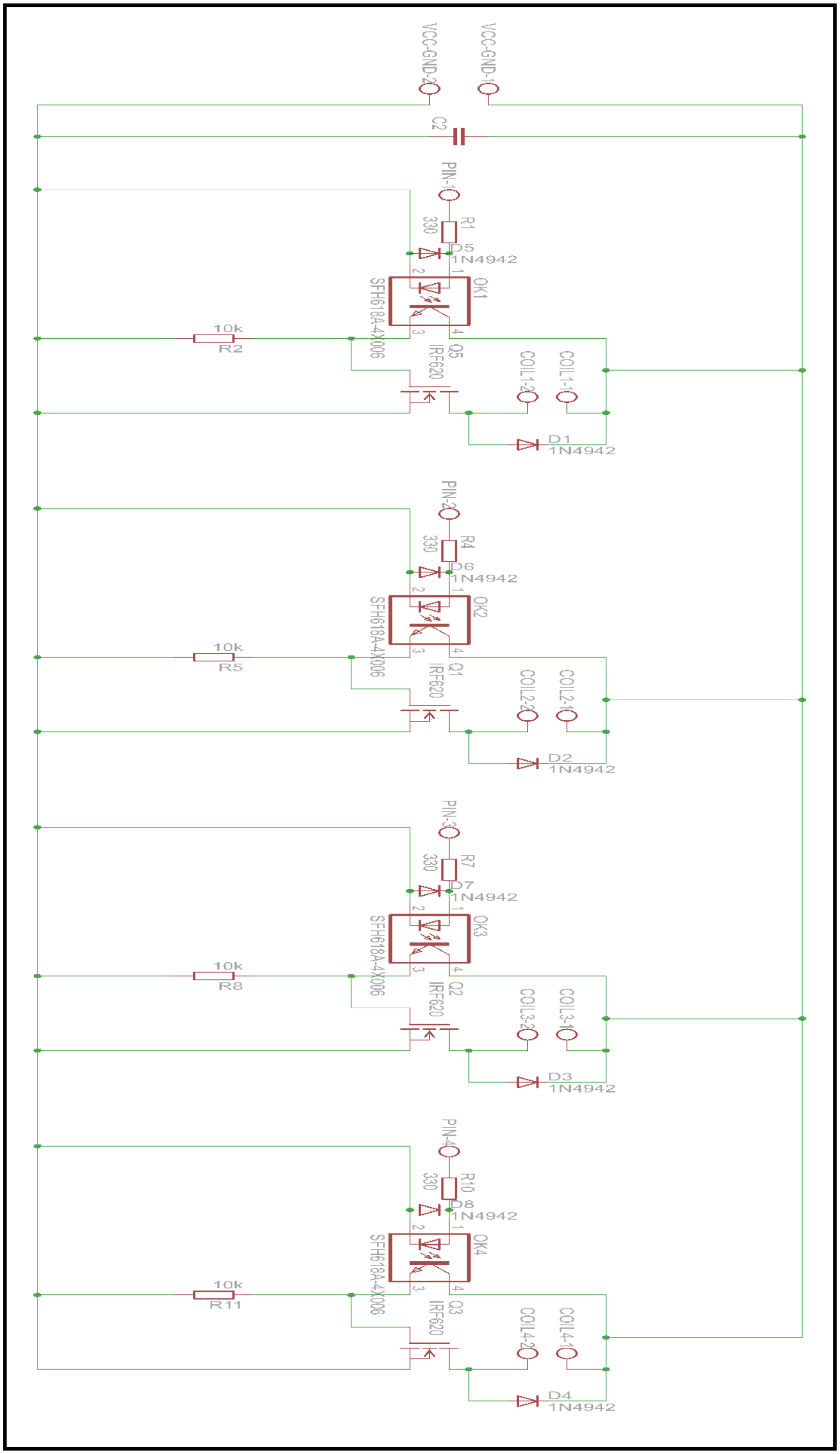
C. Atmel ATmega2560 microcontroller board schematic.



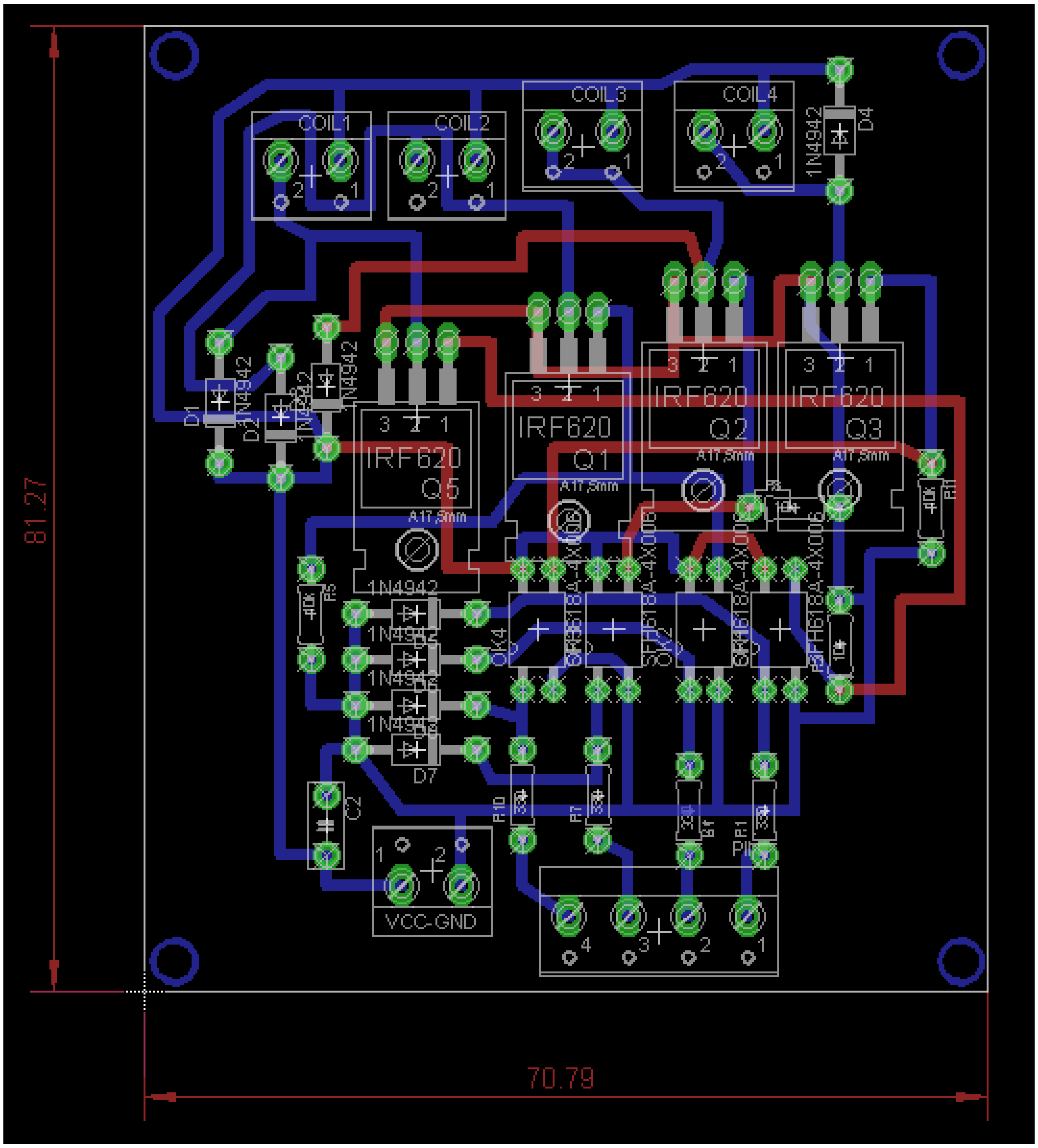
D. Atmel ATmega2560 microcontroller board schematic.



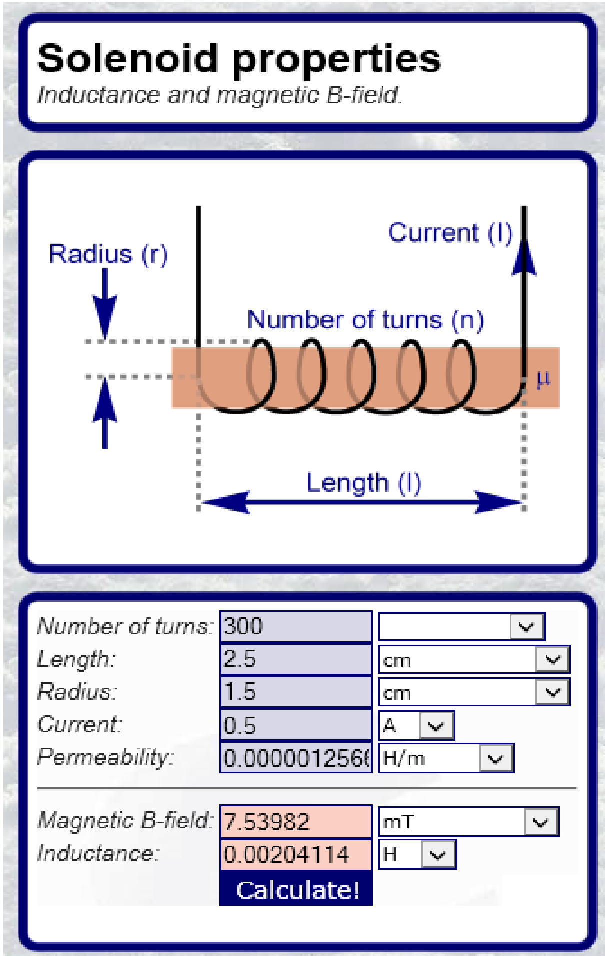
E. Schematic diagram of the circuit with MOSFET for control of for control of 4 coils



F. PCB of the circuit with MOSFET power transistors

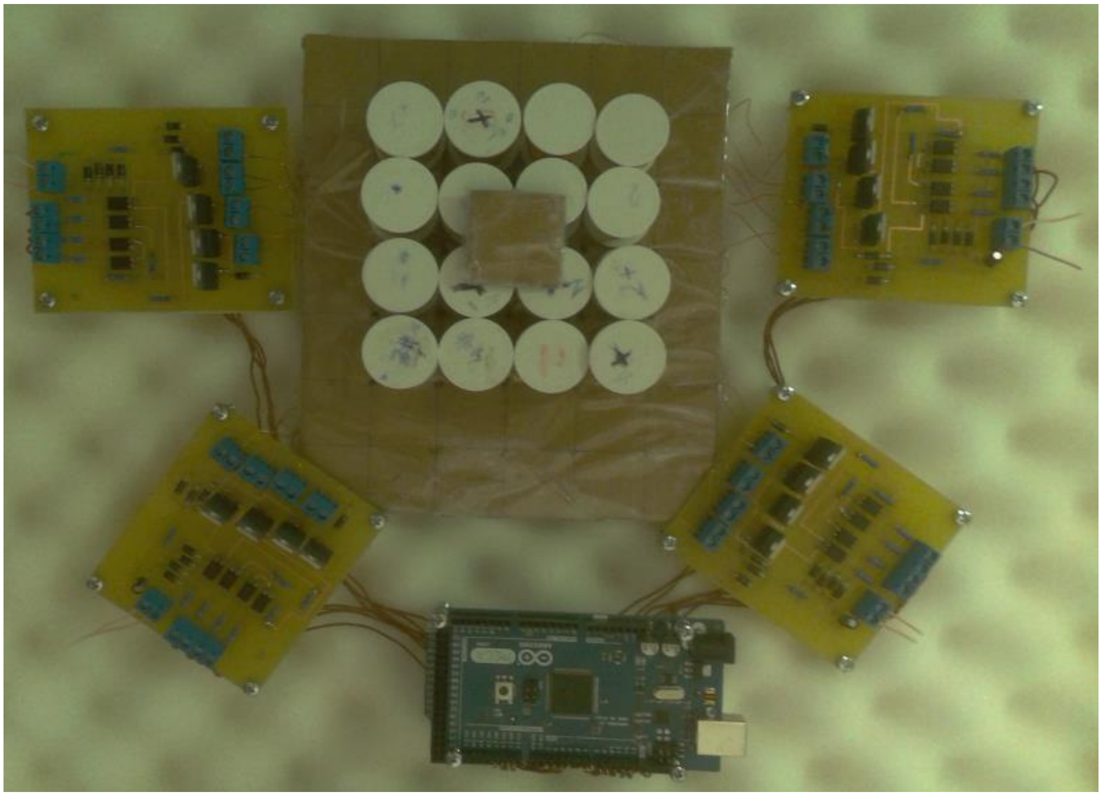


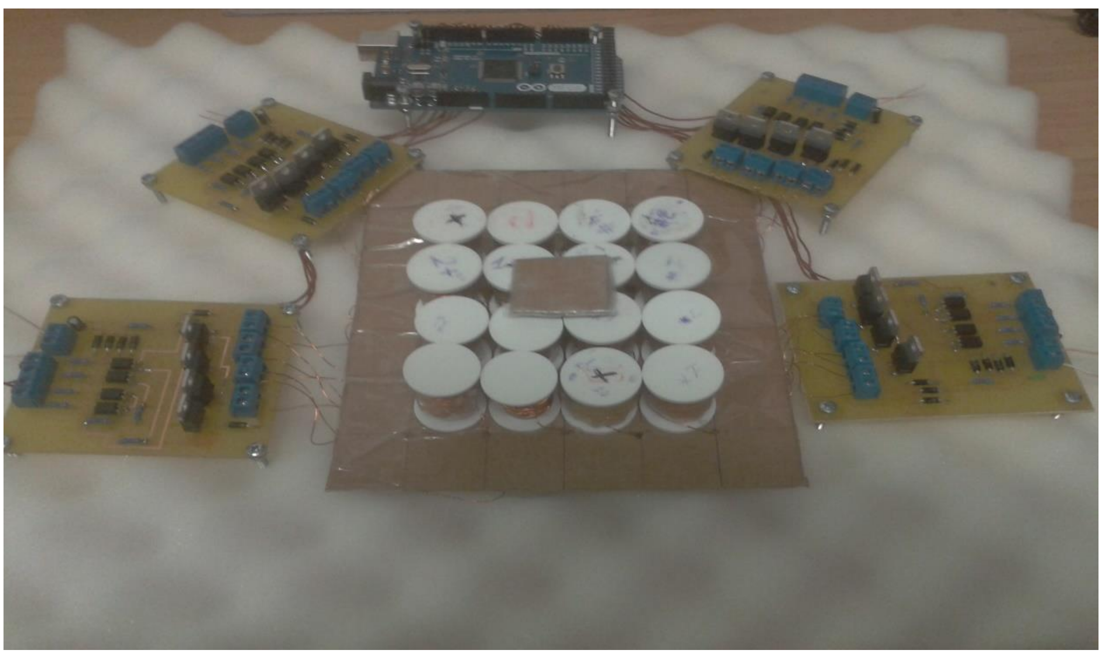
G. Solenoid properties



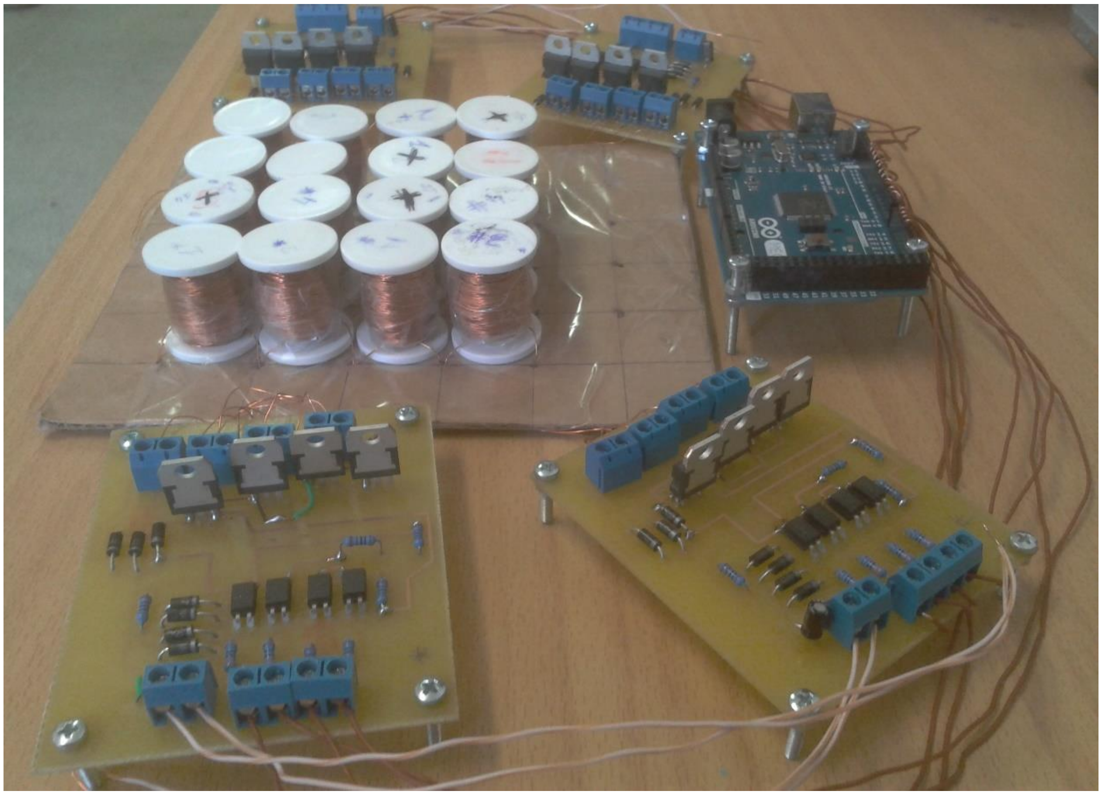
H. Stator part. Top view

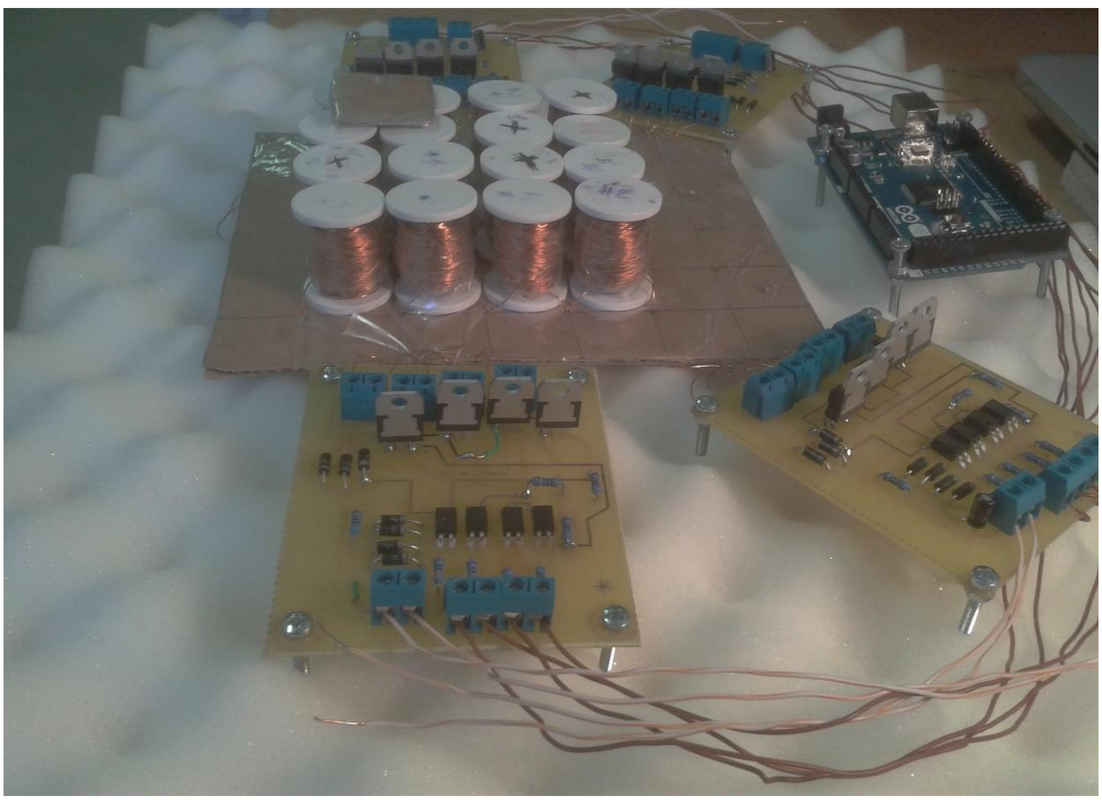
I. Picture of the constructed device. Top view





J. Picture of the constructed device. Side view





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