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Levitating lightbulb with wireless electricity transfer
Master's Thesis

Author applying for

master's sciences of technical

academic degrees

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(The reverse of the title page)

AUTHOR'S DECLARATION

I hereby declare that this thesis is the result of my independent work.

On the basis of materials not previously applied for an academic degree.

All materials used in the work of other authors are provided with corresponding references.

The work was completed under Dmitri Shvarts guidance

"May" 18 2015a.

The author

....   signature

The work meets the requirements for a master's work.

"......."....................201….a.

Supervisor

....   signature

Permit to defense

.... curriculum defense superior

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TUT Department of Mechatronics
Chair of Mechatronics System

MASTER'S THESIS SHEET OF TASK'S

Year 2015 semester 2

Student: Deniss Levskoi 122126
Curricula: MAHM02/09
Speciality: Mechatronics
Supervisor: Research Scientist, Dmitry Shvarts

MASTER'S THESIS TOPIC:
(in English) Levitating lightbulb with wireless electricity transfer
(in Estonian) Hõljuv lamp traadita elektri edastamisega

Thesis tasks to be completed and the timetable:

Nr	Description of tasks	Timetable
1.	**Decide on the goal of the thesis**	**25.03.2015**
2.	**Calculate main characteristics for main project components (electromagnet, solenoid, weight of the bulb etc.)**	**04.04.2015**
3.	**Build and program prototype for testing several questionable parts of the work**	**25.04.2015**
4.	**Model parts of the construction**	**30.04.2015**
5.	**Written part of the work finished**	**14.05.2015**

Solved engineering and economic problems: Characteristics of main project components, requirement for the construction, choosing sensors for the project, development of the control algorithms (control of the electromagnet and wireless system), synergy of two technologies that are based on electromagnetism.

Additional comments and requirements: …………………………….............................

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Deadline for submitting the theses 22.05.2015

Student ……………………….. /signature/ ………...............   date………
Supervisor……………………… /signature/ ………........   date………

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EESSÕNA

Antud töö oli algatatud autori enda initsiatiivil ja töö oli tehtud kodus. Kõik informatsioon oli enamasti võetud internetist ja raamatutest, mis on seotud elektrimagnetismiga.

FOREWORD

This thesis was started on author's own initiative and all the work was done at home. All the information was mostly gathered from internet and books related to electromagnetism.

1 INTRODUCTION

The topic of this thesis was inspired by the possibilities that electromagnetism can provide us. This work shows how the different properties of the electromagnets can be combined in order to achieve interesting results that are described in science fiction books. Although current work will doubtly find any use in everyday life, it is still possible to create in entertainment purposes and hopefully further research of this topic will yield results that will be commonly used in everyday life.

The topic of this thesis is levitating lightbulb with wireless electricity transfer. This is implemented by using induction and force of magnetic field. The properties of the electromagnets have been known to us from a long time ago. Wireless power transmission was first experimented on by Nikola Tesla, his persona is still covered by many mysteries and there exists quite a few legends about him. This shows us that this topic has been around for a long time and there are a lot of technologies that use that, however there are few uses of it in an everyday life. This project is meant to inspire research of uses of wireless electricity in different aspects. Thanks to microcontrollers the possibilities are now wider and these systems are easier to implement and control.

Currently there are no such products on the market, however there is one project on kickstarter called „Flyte", that is pretty similar to this project. Other similar product is „Crealev" levitating desk lamp, but it only uses levitation and does not use wireless energy transfer. There can be found few implementations of this projects in the internet, however when this project was started there was only one implementation availible and it had significant drawback of using optical distance sensor instead of hall sensors. Availible and similar projects can be seen in Table 1.1. The links to the project websites can be found in reference.

Table 1.1 – Existing projects

Project name	Similarity
LevLight Project [2]	Very similar – this project was found only recently, the idea and technologies are pretty similar, however it is unknown what implementation of wireless transfer was used.
Lightbulb[1]	Similar – this project is pretty old, this project major drawback is its sizes and sensor used.
Crealev[3]	This company is using a magnetic repulsion and their lamps do not

	use wireless energy transfer.
Flyte[4]	This is kickstarter project that is based on magnetic repulsion, however this one also uses wireless energy transfer. This project was published only started recently.

The LevLight project mentioned in Table 1.1 is really a similar project to this one, however not much of information is availible on the project, only basic description and some photos. The project still seems to be on it's starting point and has been around from 2012.

Flyte project seems really good and from all the similar projects it seems to be most complete and thought through, except Crealev, but that is not so similar project. This project was published recently, somewhere around april of 2015. It seems they have tried magnetic attraction, but the final design is using magnetic repulsion.

In the process of writing the thesis some parts of the project were implemented, for those purposes „Arduino Duemilanove" microcontroller board was used. In order to control the electromagnet PID control program was written using arduino editor. All the electroschemes were drawn using freeware program "EAGLE 6.2.0". The basic design schemes were done using "Solid Edge ST7 student edition".

In this work the levitation and wireless energy transfer are handled separately, first levitation system is described and then the energy transfer system is described. Prototype for levitation system was created and electroscheme for it was drawn. Some control algorithms were tested and the working one has been added to this work in appendix 1. The energy transfer system has been analyzed and some working electroschemes from found projects were shown, however the prototype for that was not created.

This work will be used as a starting point for future research and as a reference for future products.

1.1 **Aim of this work**

Currently there are many different ways of implementing different parts of this project, for example currently there exists many different levitation techniques out there. This thesis aims to accomplish following:

1) Analyze existing technologies of levitation and wireless power transfer

2) Create basic design for the levitation and wireless power transfer

3) Outline basic requirements for the construction

4) Analyze safety of the design

This work does not describe implementation of a concrete solution with concrete characteristics, because for that concrete design is needed. This work is an outline to create projects with different characteristics. Depending on some required characteristics different methods may be implemented. For example depending on the distance of the lightbulb that is required be the design, resonant and non-resonant inductive coupling methods may be applied. Another reason for not designing end product during this work is that the amount of time that is required in order to achieve the final product is too big. The reason is that this product requires a lot of tuning and experimentations. Both levitation and wireless energy transfer are really complex processes that need to be tuned to the very smallest detail, for example the geometry of the receiving coil or transmitter coil can vary the efficiency dramatically depending on even smallest of changes.

2 ANALYZING AVAILIBLE TECHNOLOGIES

The system consists of two parts, first one is levitating system and the second one is wireless energy transfer system. Those parts will be explained separately.

Main requirements to the system were outlined by author and they are following:

1) System should have as much versatility as possible
2) System should be easy to implement
3) System price should be low
4) System has to be stable
5) System should resemble real lightbulb

Using these principles author makes decisions in this project.

2.1 Existing levitation systems

There are different methods to levitate objects[5]:

- System with mechanical constraint

In this system, there are two permanent magnets that are mechanically constrained, so that they can only move vertically. These magnets are placed one above another and arranged so that they repel each other, since they cannot move sideway, one magnet levitates above other. This a really simple system, however it does not have any possibilities to control distance. Also this system does not have that impression of levitated object, so this system is not suitable.

- Diamagnetic levitation

Diamagnetic materials create a magnetic field that is opposite to external magnetic field. This causes magnets to be repelled from those materials. It should be noted, that this effect is generally very weak and only very light objects like water droplets are levitated, therefore this system does not meet requirements of this project.

- Superconductor levitation

Superconductors have strong diamagnetic effects and can levitate objects with more weight. There are trains that levitate using that system. Since superconductivity is hard to achieve and

requires special conditions this type of levitation system does not meet our system requirements.

- Currents induced in conductor

When conductor is in time-varying magnetic field, due to Lenz's law, current is induced in that conductor and opposite field to the magnetic field will be created that will levitate the conductor above magnet or vice versa. This system is not as efficient (stronger magnetic field is required) as electromagnetic suspension systems and also is more complex.

- Electromagnetic suspension[6]

In this case electromagnet is used and it's strength is controlled using feedback loop. Suspension can be achieved using either magnetic repulsion, magnetic attraction or combination of these methods. For example Kickstarter „Flyte" project uses magnetic repulsion. This project is also using this type of levitation system, however it is focused on magnetic attraction.

Magnetic attraction was picked over repulsion is because repulsion needs more complex system of control, with 3 or 4 coils. In case of magnetic repulsion system has to control object movement in X and Y axis. In case of magnetic attraction with electromagnet being above and object below magnet will move only in Z axis.

It is important to note that object can't be placed ideally in the center of electromagnet. In case of repulsion the object will be pushed further from electromagnet center. So in this case there must be other electromagnets that will be pushing object from other side to achieve balance. In case of magnetic attraction this object is being pulled towards the center. Therefore the object will eventually reach center and gain balance. In this case only once electromagnet is required.

Also other reason for choosing magnetic attraction is that author thinks that this is more natural for lightbulb to be in a position with base upwards, since lightbulbs are mostly In that position.

In order to reduce required magnetic field force generated by electromagnet, magnets can be placed into the object. It is best to use magnets with strong magnetic field, for example neodymium magnets. This will also make control easier.

2.2 **Object position sensing system**

There are multiple levitation systems out there and different projects use different methods. Following systems were found on similar projects:

- Horizontally placed IR (infrared) sensor

This kind of system is used in Feedback Instruments Limited experiments[7]. The idea can be seen on Figure 2.2.1. This system has a serious drawback, in this kind of setup the area that sensor can sense in is limited across Z axis that means that ball's positions are also limited by the sensor. Second limitation of this system is that if in the way of IR sensor some obstacle appears, for example a fly or a hand, the sensor will not be able to sense ball's position. There are other similar projects, where instead of IR sensor photo sensors are used that sense different LED colors, that are on the other side of the object, however these systems have same limitations.
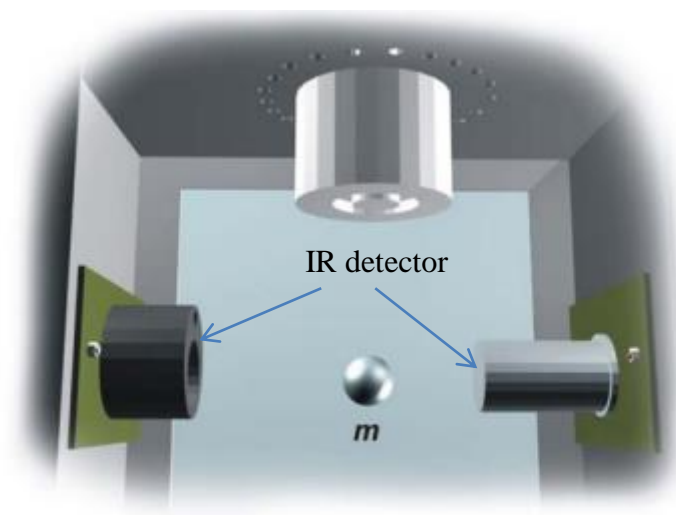

Figure 2.2.1 – Feedback Instruments Limited experiment[7]

- Vertically placed IR sensor

One example of such project is done by Jeff Lieberman[1]. His project is also levitating lightbulb. In this project IR sensor was placed under the lightbulb and the electromagnet above the lightbulb. This method has no limitations for positioning of the object, however it makes the installation more difficult. The drawback of having random obstacles appearing is still there.

- Hall effect sensor placed on the electromagnet

In author's opinion this method is the best and most versatile, meaning it is the most suitable for this project. In case of this method, the sensor is placed on electromagnet. This is best, because construction will be more ergonomic and take less space. Also sensor is indifferent to obstacles, because it senses magnetic field strength created by the magnets in the object. Although there is a problem, that the electromagnet also generates magnetic field, it can be resolved by placing the second sensor above the electromagnet, this way the sensor that is on top of the magnet can sense strength of the magnetic field created by electromagnet and using that information we can get the position of the object. It is also possible to use only one sensor, we can map electromagnet's magnetic field strength on different current values and later approximate it's strength. But using two sensors is better, because it makes system more stable and accurate.

2.3 Wireless energy transfer system

Wireless energy transfer means transfering energy from one circuit to another wirelessly (through air). There are different methods for this, for example inductive method uses induction to transfer electricity from transmitter coil to receiver coil.

Right now there are multiple possibilities to transfer energy wirelessly. Our system does not need to transfer big amounts of power it only needs to transfer energy to power up few LEDs. For electricity transfer mostly are used inductive and capacitive coupling methods.Those methods can be resonant and non-resonant. In case of resonant circuits the range increases multiple times compared to non-resonant. Resonant circuits are more difficult to implement. [12][13][14]

Depending on the system requirements non-resonant coupling can be used. If the required transmission range is over the diameter of the antenna then this method cannot be used, however if it is equal or less than that then this methods range will suffice. For example in case of prototype created for this project, this range would suffice since electromagnet is weak and cannot operate beyond 5cm distance.

Capacitive coupling uses electrostatic induction. Power is transmitted between electrode plates that form a capacitor. An alternating voltage that is on transmitting plate causes alternating potential on receiving plate and that causes alternating current to flow in the receiver circuit. The transferred power depends on the frequency and capacitance between the plates.

Inductive coupling uses electromagnetic induction method to transfer energy. In this case power is transferred between coils of wire. The varying magnetic field of transmitter coil induces electromotive force across a reciever coil. Varying magnetic field in the transmitter coil is created by an alternating current. The current induced in reciever coil is also alternating. The transferred power depends on the frequency and mutual inductance.

Since capacitive coupling relies on electric field, it becomes hard to use it, since there are multiple health issues associated with electric fields being harmful to human body. Also capacitive coupling is harder to implement and requires higher voltages. Those are the reasons why in case of this project inductive coupling will be used.

Resonant inductive coupling is an inductive coupling between two resonant circuits and both circuits resonate at the same resonant frequency. In case of this project the resonant version will be viewed, because it allows more variety of different versions of this project.

3 LEVITATION DEVELOPMENT

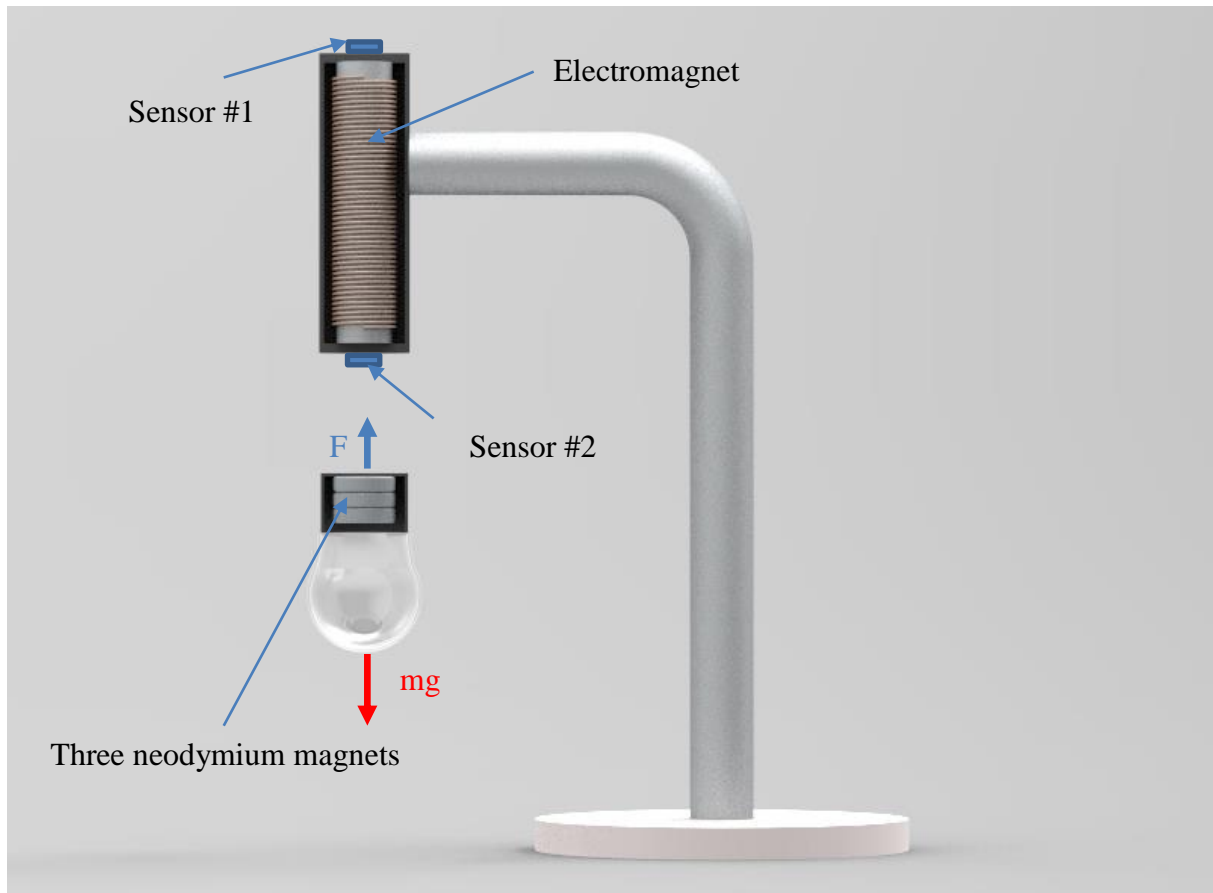## 3.1 **Basic schema of levitation**

Figure 3.1.1 – Basic scheme of the levitation part of the project

On Figure 3.1.1 it is possible to see the basic scheme of the project. It should be noted that this is not the design of the final product. The electromagnet holder can be made to look similarly to ordinary lamp and instead of holding lightbulb it will hold electromagnet. On electromagnet there are hall-effect sensors on top and on bottom. Three neodymium magnets are hidden inside the lightbulb. In this setup lightbulb can only move upwards and downwards.

If electromagnet's height plus lightbulb distance from electromagnet is big enough then the magnetic field from neodymium magnets will not reach the sensor that is on the top.
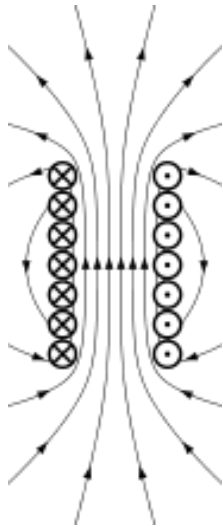
3.2 Levitation implementation principle

Figure 3.2.1 – Cross-section through the center of the coil and magnetic field[41]

In order to understand the concept behind all the control, first the operation principles of electromagnet must be understood. Electromagnet is a solenoid that has a magnetic core made from ferromagnetic materials, such as iron for example. Although solenoid can produce magnetic field even without the magnetic core, by adding it the field and forces that are produced by it are amplified.

The shape of the magnetic field depends on the shape of the coil, there exist many different types of electromagnets as an example there is a toroidal electromagnet and it's magnetic field is different from solenoid magnetic field. However solenoid around a ferromagnetic core is most common type of electromagnet and it is suitable for our purposes, On Figure 3.2.1 is illustrated how the magnetic field lines flow inside and outside the solenoid. In case of this project since object is placed below the solenoid only force along z axis remains, other forces cancel each other out. If object is slightly misplaced, magnetic field will align it to the center itself.

Force that magnetic field has is described by Lorentz force law. The law is defined by equation (3.2.1)[17]. From that it is possible to see that force depends on magnetic field where the charge is.

$$\vec{F} = q\vec{v} \times \vec{B} \qquad\qquad (3.2.1)$$

Where q – Electric charge

$\quad\quad \vec{v}$ – Velocity

$\vec{B}$ – Magnetic field

Following Lorentz law force that pulls permanent magnets up is dependent on the magnetic field of electromagnet and it's own magnetic field. In order to control the position of the lightbulb it is possible to control force that pulls it up by controlling electromagnetic field of the electromagnet.

In order to understand the magnetic field outside the electromagnet along it's axis it is possible to use Biot-Savart's Law show on equation (3.2.2)[20][21]. Basically this law describes magnetic field generated by electric current. It uses line integral over path C where integral flows. From 3.2.2 it is possible to calculate a magnetic field created by a loop of wire at distance z. Calculations are shown on equation (3.2.3). From that it is possible to construct equation for solenoid, calculations for that part are shown on equation (3.2.4). However equation (3.2.4) does not give electromagnetic strength for the point with distance z, in order to get a point in the distance z equation (3.2.5) is used. Idea behind that is that first the solenoid which length is calculated until the point z and then the part that is air is substracted from it.

$$B(r) = \frac{\mu}{4\pi} \int_C \frac{Idl \times r'}{|r'|^3} \qquad (3.2.2)$$

Where B – Magnetic field (T)

μ – Relative permeability (Tm/A)

I – Current (A)

r – Position (mm)

l – Length of the wire (mm)

r' – Displacement vector from the wire element l to the point at which magnetic field is computed

$$B(z) = \int \frac{\mu Idl sin\theta}{4\pi r^2} = \frac{\mu R^2 I}{2(R^2 + z^2)^{\frac{3}{2}}} \qquad (3.2.3)$$

Where R – Loop radius (mm)

z – Distance from the point where B is calculated

$$B = \int \frac{\mu R^2 I}{2(R^2 + l^2)^{\frac{3}{2}}} ndl = \int \frac{\mu sin3\varphi I}{2R} n \frac{-rd\varphi}{sin\varphi} = \frac{\mu Inl}{2\sqrt{R^2 + l^2}} \qquad (3.2.4)$$

Where l - Length of the electromagnet

n – Number of windings

$$B = \frac{\mu n I}{2}\left[\frac{l+z}{\sqrt{(l+z)}} - \frac{z}{\sqrt{z^2+R^2}}\right]$$
(3.2.5)

The magnetic field inside a solenoid is shown on equation (3.2.6)[15] and outside the solenoid on equation (3.2.5). As it is possible to see from those equations the strength of electromagnetic field depends on current, number of turns in the solenoid, length of the solenoid and relative permeability, which is equal to relative permeability of the core multiplied by permeability of free space. From all of these components the easiest one to manipulate is current. So control process will use current to manipulate strength of magnetic.

$$B = \mu \frac{N}{l} I$$
(3.2.6)

Basic idea of operation is that sensors read the position of the lightbulb and feed that information to the microcontroller then microcontroller processes that information and outputs a current to the electromagnet. This process is shown on Figure 3.2.2.
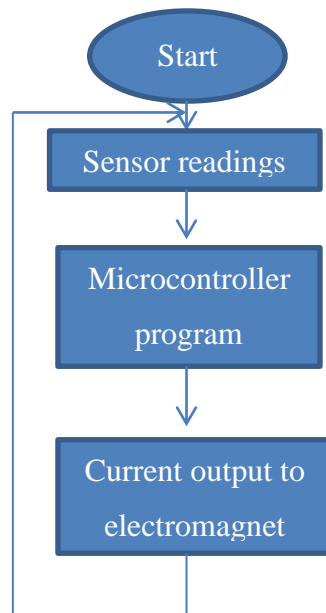

Figure 3.2.2 – Levitation process flowchart

3.3 Choosing electromagnet

Choosing electromagnet is a fairly hard task, since the calculations of the force between electromagnet and a magnet are complex. The force F, that is shown on Figure 3.1.1, has to

be more than weight of the lightbulb at maximum operational distance. For the maximum weight in this project 200 g will be taken. That means *F* has to be more than 2 N.

There are some research done on calculating forces between thick coil solenoids and permanent magnets, as an example work done by Will Robertson, Ben Cazzolato and Anthony Zander[22]. In that work they present four methods to calculate the force applied on cylindrical permanent magnet by thick coil solenoid, however those methods cannot be applied to electromagnet and calculations of that scope do not fit in the scope of current project. That is why in current project the electromagnet was picked by experimental means.

For prototype several electromagnets were created by winding insulated wire on a magnetic core starting with the first electromagnet 300 windings ending with 1200 windings. However none of created magnets could produce good enough magnetic field for this project. Last electromagnet could still lift around 50g. The electromagnets were winded on iron core and the length of the magnet is 70mm. When supplying more than 1A the electromanget starts heating too much.

In order to have electromagnet sufficient for current project, it is better to get an electromagnet which working voltage is 12V. They can be purchased from different sources, however cheapest are on online stores like aliexpress. Example of such electromagnet can be seen in Figure 3.3.1 and

Table 3.3.1. It can hold up to 25 kg of weight on it, however it should be noted that with distance the force decreases drastically, so when distance is around 40mm the pulling force will be a lot smaller.

Figure 3.3.1 – Electromagnet [42]

Table 3.3.1 – Electromagnet characteristics

Type	D	d	H	M	P	L	Power	Force	Weight
	mm	mm	mm	-	mm	Mm	W	N	g
HCNE$_1$-P25	25	10	20	M4	6	200	4	50	50

3.4 **Levitation control implementation**

In this project the control is implemented using microcontroller. Since electromagnet requires more current than normally microcontrollers can supply, the transistor is used. Basic current control schematic is fairly simple it can be seen on Figure 3.4.1.
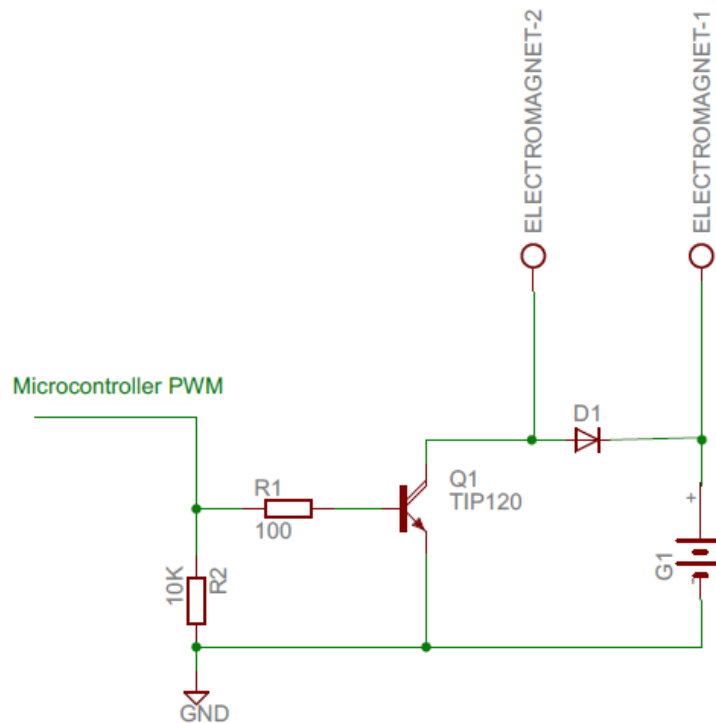

Figure 3.4.1 – Electromagnet control scheme

As seen in

Table 3.3.1 the power that is consumed by the electromagnet is 4W and the voltage is 12 V. Generally microcontrollers are not able to output that much of voltage. That is why as can be seen on Figure 3.4.1, the control is implemented using transistor.

Transistor can be controlled by pulse-width modulation (PWM) signal, that microcontroller generates. PWM signal is a method of outputting analog signal by digital means. Signal generated by PWM method is a square wave. Meaning the signal is turned on and off and

using that method the average of voltage and current fed to the load can be controlled. Example of such signals can be seen on Figure 3.4.2 – PWM signal of microcontroller. The frequency of such change of state of signal has to be high, so that the controlled load will not be able to react. For example, when controlling LED if frequency is not high enough at 50% duty cycle the LED will be blinking instead of being dimmed.
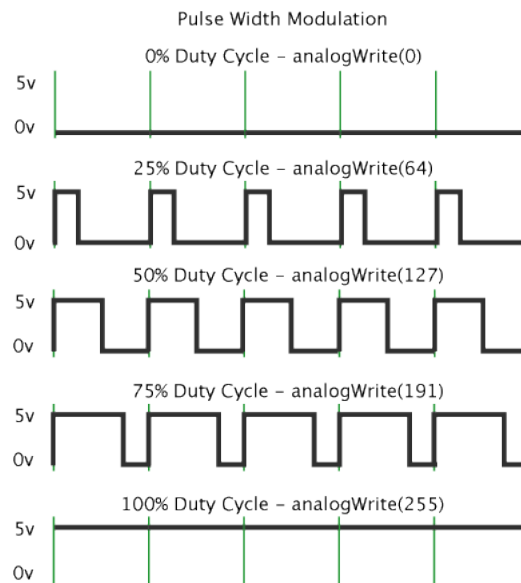

Figure 3.4.2 – PWM signal of microcontroller[23]

Transistor has 3 pins: base, collector, emitter. Transistor image is shown on Figure 3.4.3. When PWM signal is sent on the base of transistor, it controls amount of current that can be transmitted from collector to emitter. In order to pick correct transistor it is required to understand in which conditions it will work. In this case, the collector-emitter current will be under 0.5 A, current-emitter voltage will be 12V. For purposes of experimentation when different electromagnets were made the TIP120 transistor was used, because of its high collector-emitter current and voltage. In cases of some electromagnets more than 1A current was measured and this transistor works with current that is less or equal than 5A. Also this transistor is linear, meaning that the current in the gain is proportional to the collector-emitter current. They proved to be fairly stable and sturdy In case of this project the linear transistor was picked because it makes the operation of control algorithm more transparent. All of the characteristics for this transistor can be found in Appendix 2. To this point no better transistor was found in local stores and „Farnell element14" online store, so this transistor will be used for this electromagnet aswell.
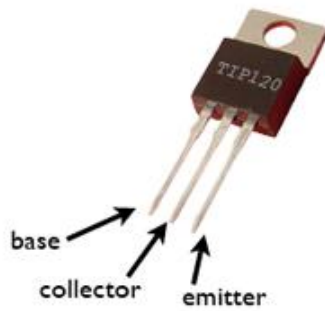
Figure 3.4.3 – Transistor[43]

In Figure 3.4.1 there is a diode between electromagnet pins, it is required because when electromagnet is inductive and when it is turned off some of the induced current will try to run into collector and then into microcontroller, however diode protects against that. Diode that was picked can handle 2A current. The resistor between microcontroller and transistor is for the same puprose, to protect against current that passes through transistor.

In this project transistor can be replaced with H-bridge to enable reversing of current so that the magnet could be repelled. There is a problem, that when a magnet gets too close to electromagnet it will be attracted to because of the ferromagnetic core, even if the electromagnet is turned off. So in case, when the distance between lightbulb and electromagnet has to be smaller than that, the H-bridge should be used.

After the main scheme has been decided it is now possible to choose microcontroller and scheme connected to it. For the purposes of prototype the "Arduino Duemilanove" was used. It is a microcontroller board based on ATmega168 or ATmega 328 microcontroller. The board can be seen on Figure 3.4.4. Main characteristics of the microcontroller are shown on Table 3.4.2. The microcontroller that was used in this project is ATmega328. The electric scheme can be seen in appendix 3. This microcontroller board was able to handle this type of complex control and was able to react fast enough.

Table 3.4.2 – Arduino Duemilanove characteristics[24]

Microcontroller	ATmega328
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	14 (of which 6 provide PWM output)
Analog Input Pins	6

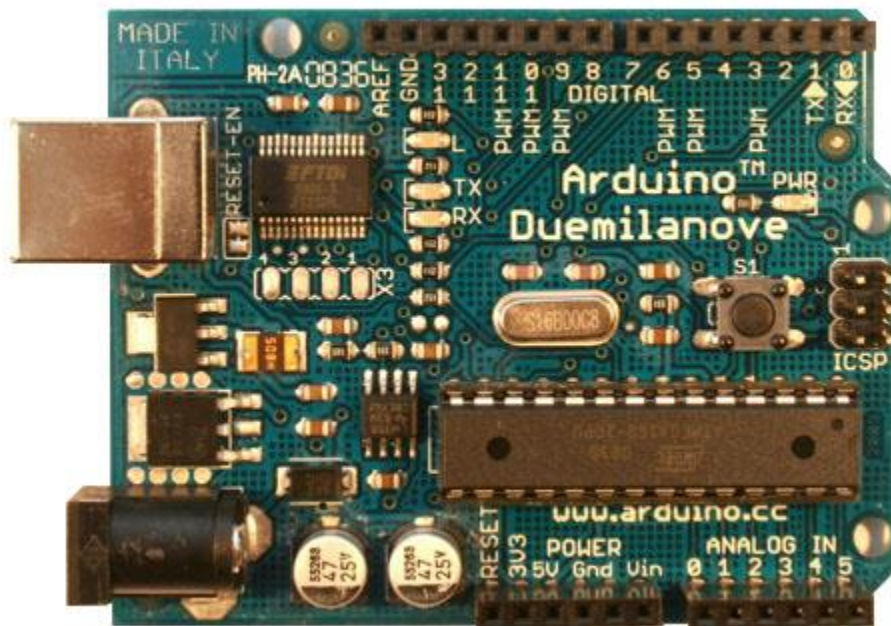|	
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	32 KB (ATmega328) of which 2 KB used by bootloader
SRAM	1 KB (ATmega168) or 2 KB (ATmega328)
EEPROM	512 bytes (ATmega168) or 1 KB (ATmega328)
Clock Speed	16 MHz

Figure 3.4.4 – Arduino Duemilanove[24]

It was decided to use same microcontroller for this project. On "Farnell element14" store the ATmega328P microcontroller was found. The pinout for that microcontroller is shown on Figure 3.4.5. Not all output and input pins are required. For the transistor PD3 pin will be used. It is a PWM output pin. In order to work properly the microcontroller needs 5V regulator. It will take the incoming current and transform it into 5V. For this task LM7805 voltage regulator was picked. More information about this regulator can be seen in Appendix 4. In order to create 16MHz clock signal the crystal oscillator is used. This can be seen on final electic scheme of the project in Appendix 5. Final electric scheme of the prototype can be seen in Appendix 6. It should also be noted, that ATmega328P can be programmed using arduino board.
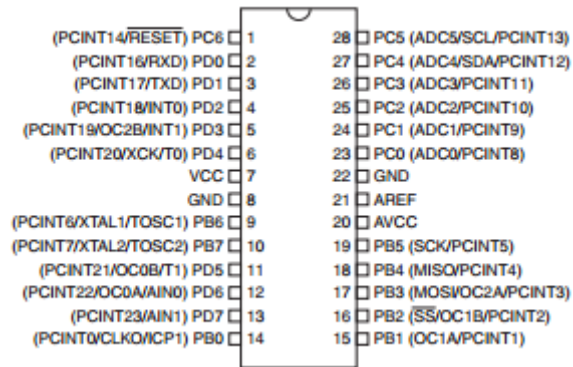
Figure 3.4.5 - ATmega328P pinout[25]

For sensing object distance from electromagnet hall-effect sensor is used. The sensor that was picked is SS496A, it can be seen on Figure 3.4.6. One of the important characteristics is that this sensor output is linear. Since the control of this system is complicated and the system itself is not linear, it is important that the sensor output is linear. Another important characteristic is the range of magnetic field that is measured, in this case it is -400 to 400 gauss. Since the input is only 5V it can be powered by the voltage regulator that powers microcontroller. The dimensions of the sensor are very small and it can be easily placed on the electromagnet. Sensitivity of this sensor is 0.60 to 1.25 mV per gauss. This sensor was tested with the prototype and it's operational range and sensitivity are enough for this project
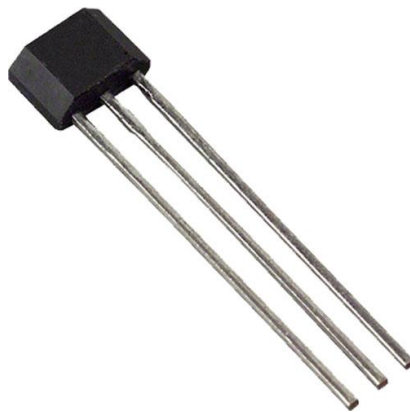

Figure 3.4.6 – hall-effect sensor[44]

3.5 Levitation control algorithm

The algorithm of the control is based on changing the strength of electromagnet's magnetic field to move the object as close to the set point as possible. This task is pretty complex, because one of the main requirements is that the levitation must be as stable as possible and seem to be suspended in the air, rather than oscillating, therefore the control must react almost instantly to even slightest changes of the position.

For testing purposes the prototype was built and different algorithms were tested. However the most efficient one was PID controller. PID controller output is a feedback mechanism, it tries to bring process value to a setpoint value by adjusting a variable. In case of this project it adjusts electric current running through an electromagnet, gets sensor readings and calculates error, after that it adjusts the current again.
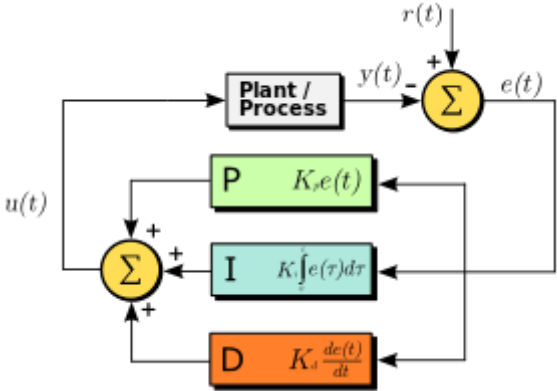

Figure 3.5.1 – A block diagram of a PID controller feedback loop[45]

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{d}{dt} e(t) \qquad (2.3.1)$$

where Kp - Propotional gain

Ki – Integral gain

Kd – Derivative gain

t – Time

e – Error

τ – Variable of integration

On Figure 3.5.1 and equation (2.3.1)[10] is shown the idea behind the PID controller. The controller consists of 3 components: proportional component, derivative component and integral component. This algorithm will bring the current to the value needed to hold the magnet at set distance.

Proportional component depends on present error and is equal to setpoint value minus present value multiplied by proportional gain. When manually tuning the controller, this is normally the first component that is tuned.[8][9]

Derivative component depends on the rate of change of process values. Basically this component tries to predict system behavior therefore it improves stability of the process. It is calculated by multiplying slope of the error by derivative gain. [8][9]

27

Integral component is the sum of all errors over time and is basically the accumulated error. This component moves process value closer to setpoint value and it also removes any steady-state error. It is calculated by multiplying integral gain by the sum of all errors. [8][9]

The prototype has manually tuned PID system. First derivative and integral parameters were set to zero and proportional gain was increased until the system started oscillating. Next the derivative part of the process was tuned, in case of this project the derivative part is really big, around ten times larger than the proportional component. As the last step the integral component is implemented, it allows to change the setpoint values while system is active.

For the purpose of tuning the parameters were controlled from computer. For that serial port was used. There are separate commands for output of all the parameters and separate commands for changing different parameters. The code can be seen in appendix 1.

In reality there are different methods of tuning PID controllers. For example Ziegler-Nichols[7] method or Cohen-Coon method. Usage of those methods is advised to tune the PID controllers.

Ziegler-Nichols method is pretty simple, as described previously, first integral and derivative components are set to zero. The proportional value is increased until the system starts oscillating, the proportional value that is acquired is ultimate gain value (Ku). Another important value is oscillation period required for one full oscillation (Tu). After getting these parameters it is possible to get all gains from the Table 3.5.1.

Table 3.5.1 – Ziegler-Nichols tuning rule table[7]

Rule Name	Tuning Parameters		
Classic Ziegler-Nichols	Kp = 0.6 Ku	Ti = 0.5 Tu	Td = 0.125 Tu
Pessen Integral Rule	Kp = 0.7 Ku	Ti = 0.4 Tu	Td = 0.15 Tu
Some Overshoot	Kp = 0.33 Ku	Ti = 0.5 Tu	Td = 0.33 Tu
No Overshoot	Kp = 0.2 Ku	Ti = 0.5 Tu	Td = 0.33 Tu

The control system can be further developed by adding open-loop control, however the problem is that the interaction between electromagnet and magnet is complex. If the developed system will have a need for better control, then further development of the control system can take place, there are possibilities of modelling the problem, for example there is Gilbert's model, however in case of this project it is not necessary, PID control is sufficient.

3.6 Levitation control program

The algorithm of this project is shown in Figure 3.6.2. It is based off the program written for prototype in Appendix 1 but without unnecessary elements that were there for debugging and PID constants tuning.

While testing algorithm it became apparent that the arduino programm was not responding fast enough to the changes in magnet position. Different ways to make it faster were researched. The solution has 2 steps: make *analogread* command faster and make PWM digital output faster.

Arduino analog-to-digital converter (ADC) converts incoming analog signal into digital value. In our case analog signal is a reading from hall-effect sensor. The clock speed of ADC is lower than the core's clockspeed, it is lowered by a prescaler value. In a default mode the prescaler value is 128. That means, ADC clock speed is *16MHz/128=125KHz*. The analog-to-digital conversion takes 13 clocks and that means that the sampling rate is under 10KHz. In the documentation of the ATmega328P it is said that ckickspeed can be raised to 1MHz without significant resolution losses. For that the prescaler value is set to 16, meaning *16MHz/16=1MHz*. In order to set prescaler to 16 the bits 2, 1 and 0 of a ADCSRA address in a register have to be changed to 1, 0 and 0. The prescaler values corresponding to different bit values is shown at Table 3.6.1. When prescaler is set to 16, the *analogRead* command is executed approximately 7 times faster.

Table 3.6.1 – Prescaler value table[26]

ADPS2	ADPS1	ADPS0	Prescaler
0	0	0	2
0	0	1	2
0	1	0	4
0	1	1	8
1	0	0	16
1	0	1	32
1	1	0	64
1	1	1	128

PWM signal had to be changed aswell. The function provided by Arduino *analogWrite* does not pwm signal that would satisfy the needs of this project. So that means the values in register will have to be changed directly. The chosen output pin is 3, so the changes will be applied to that pin. Mode of operation was decided to be changed to phase-correct mode. This generates symmetric PWM signal. In this case the timer starts counting from 0 to 255¸once the set value is hit, the pin output is toggled, after timer reaches 255 it starts counting down and when the set value is hit the output is toggled once again. The comparison to fast mode can be seen in Figure 3.6.1

As in the case with ADC there is a prescaler value that controls PWM timer clock. The prescaler value that was picked in this case is 8. Since the phase-correct mode was picked clock speed is divided by additional 2. So the frequency of the output is *16MHz/255/2/8=3.9KHz*. The bits that are responsible for the prescaler in this case are CS22, CS21 and CS20. The prescaler values can be seen in Table 3.6.2. Setting WGM20 bit to 1 enables the phase-correct mode.

Table 3.6.2 – Prescaler of PWM timer[26]

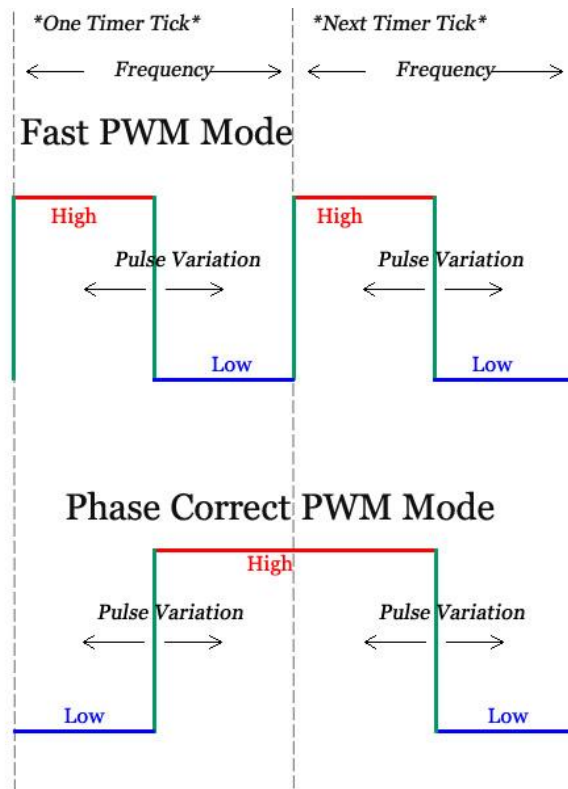| CS22	CS21	CS20	Prescaler
0	0	0	None
0	0	1	None
0	1	0	8
0	1	1	32
1	0	0	64
1	0	1	128
1	1	0	256
1	1	1	1024

Figure 3.6.1 - Mode comparison [27]

The program checks if 1ms has passed before starting each operation loop cycle, this is required to ensure same step between each loop cycle. This is required for PID integraal component and derivative component to be valid. So if 1millisecond has not passed it waits until it passes.

At the beggining of each loop sensor values are read. In order to get the distance of the object from the electromagnet the values of sensors are substracted. This is necessary because the electromagnet has an electromagnet field and it is not linear toward the current value. So basically second sensor is used to substract the unnecessary field value from the first sensors value.

Using the substracted value of sensors the PID controller values are calculated. The value of proportional error value is calculated by substracting current value of sensors from setpoint value. The derivative value is calculated by substracting current proportional error value from proportional error value obtained from previous loop cycle. Integral value is obtained by simply summing all of the proportional error values and then constraining the value between -255 and 255.

The output value is obtained by multiplying each calculated PID value to their constants that were obtained during the tuning period. The value must be constrained between maximum and minimum of the output, that means between 0 and 255. To output the value the ordinary means of *analogWrite* function of Arduino cannot be used. To output the value the value must be written directly into compare register.

This program can be further developed, this version is bare minimum to make the system work. For example adding additional controls to electroscheme, like buttons or potentiometer, can enable the control of setpoint, meaning the lightbulb can be made to move along Z axis. Int he prototype program in Appendix 1 the setpoint is set in the value that is returned by ADC, however using the sensitivity it is possible to convert the adc output into distance and make the setpoint value to be in millimeters.

As mentioned before the control system can be made more complex and open-loop control can be added, to make the system more stable and more resilent against disturbences. However this does not fir in the scope of this project, because the calculations are truly complex and it is even more complex to fit them into controller, since the calculations need to be optimized to the maximum. Some approximation systems may be adopted, like recording values at different distances and interpolating them later.
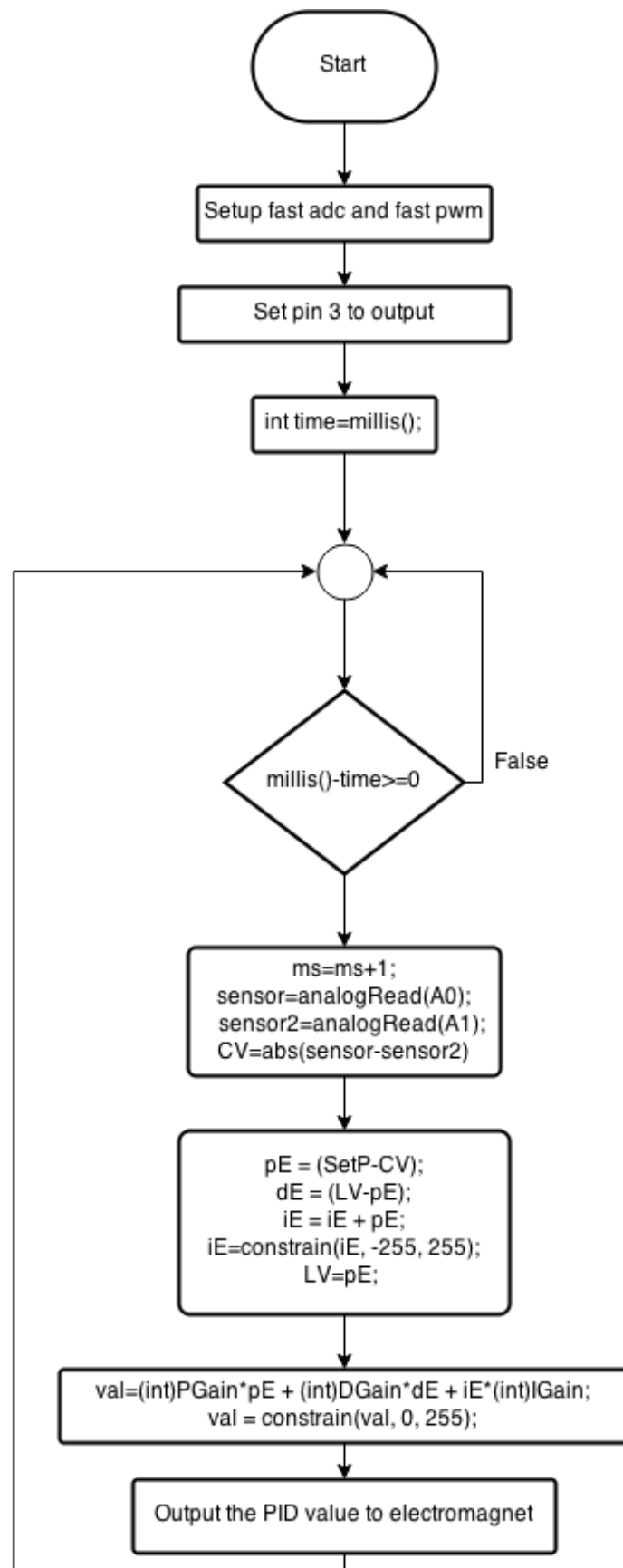
Figure 3.6.2 – Control algorithm

3.7 **Prototype programm additional parts**

In the prototype programm there are several parts that were used solely for tuning purposes. One of those parts is serial communication between computer and the arduino. During experiments Arduino was powered by USB port. Through same USB port the communication takes place. Using that it is possible to debug the programm outputting the values into the serial port. On Figure 3.7.1 the communication window is shown. The upper input that is next to button „Send" is used to send commands to serial port and below that is the information returned by the serial port.
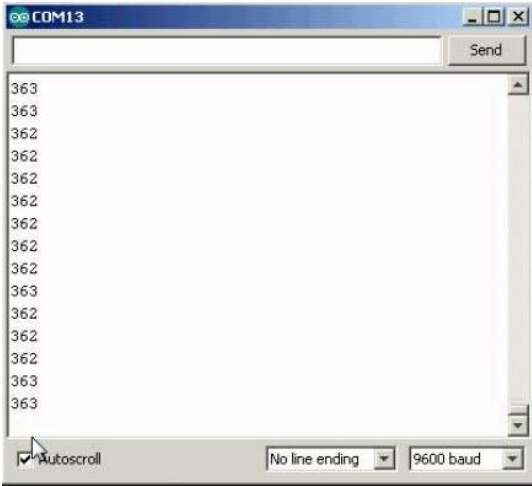

Figure 3.7.1 – Serial port communication window

In the program serial port was used to change values of following system characteristics: derivative constant, integral constant, proportional constant and setpoint. This was done by sending character into the serial port to select what parameter to change and after that the numerical value of the constant was sent. There also is a command to output current system state.

Potentiometer in the prototype is used to change value that was added to the output value. It was used to aid the tuning process.

4 ENERGY TRANSFER DEVELOPMENT
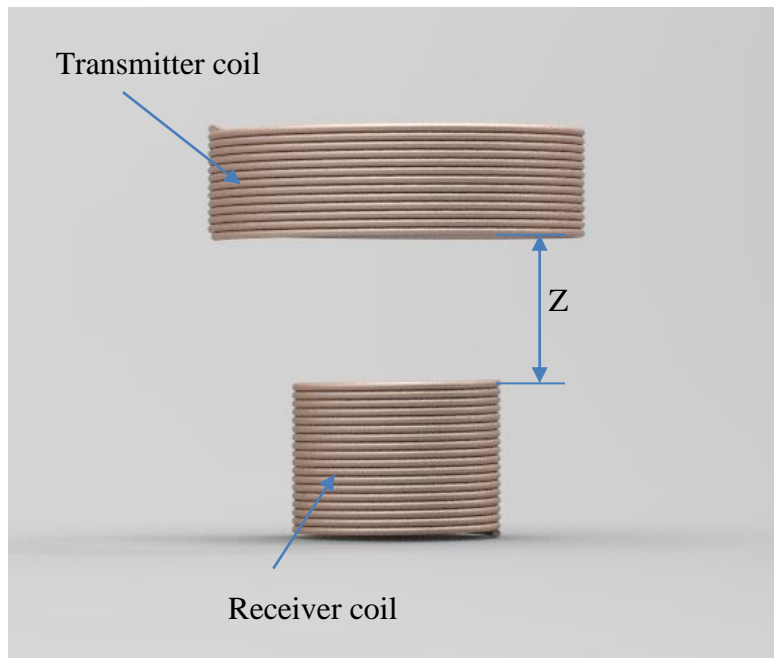
4.1 Basic schema of the energy transfer

Figure 4.1.1 – Energy transfer basic schema

Wireless energy transfer means that the energy from the transmitting device is transmitted to the reciever device without using any solid conductors. The power is transmitted over the air and the obstacles between devices, for example a hand or a fly, do not prevent energy from being transmitted. In our case the induction is used, that means that the energy is transfered using alternating magnetic fields.

In this project resonant inductive coupling is used. That means that there are two coils, just like on Figure 4.1.1, they are resonant RLC coils and are tuned to resonate at one frequency. The idea of using resonant RLC circuits is that when the energy is placed into circuits it dies away slowly. When the transmitter coil starts ringing with oscillating current the oscillating magnetic field is created. It is known from Faraday's law that changing magnetic field creates electromotive force that drives current. That means when the receiver RLC coil is placed into changing magnetic field of transmitter coil, the electricity is being induced in the reciever coil and because reciever coil is resonant RLC coil, the energy dies away slowly.

The reason why resonant circuits or tank circuits act in this way is because of the inductor and capacitor elements. When charged capacitor is connected to the inductor the circuit starts

oscillating. The electric field of the capacitor depends on the voltage and magnetic field of the inductor depends on current. That means when the charged capacitor is connected to the inductor, the current starts flowing through the inductor creating magnetic field reducing the charge and voltage of the capacitor. When the capacitor is empty the current of the inductor will remain as it was before because for it to change the voltage must be applied. At some point, since the current still flows the capacitor will acquire the charge of opposite sign and while it acquires the charge the voltage rises, since the current in the inductor is opposite to the voltage, the current in the inductor is falling. Once current is zero and the magnetic field is dissipated the capacitor is charged again but with opposite polarity. The current stops for a moment and then starts again. This is how the oscillations flow. This proccess would be infinite If there was no resistance, however wire has resistence, therefore this proccess dims with time

The efficiency of wireless energy transfer is very complex topic and it is also not linear. Designing such systems requires a lot of experiments and experience. During this project no prototype for energy transfer system was created, since this needs more time. However the existing methods and projects of similar type were analyzed.

4.2 Transmitter coil design

There are many different techinques to make an oscillating circuit. Depending on the required distance different circuits can be used. Example of such circuit is Colpitts oscillator[30]. There exist several projects of wireless energy transfer in the internet that use the colpitts oscillation method. As with most such circuits it uses a transistor to produce a sinusoidal output.

Example of such circuit can be seen on Figure 4.2.1. The tank circuit shown is the resonant circuit that was explained above. Frequency of such circuit is determined by equation (4.2.1)[31].

$$f_r = \frac{1}{2\pi\sqrt{LC_T}}$$
(4.2.1)

Where L – Inductance of the inductor (H)

   C_T – Capacitance of C1 and C2 connected in series (F)

$$C_T = \frac{C_1 * C_2}{C_1 + C_2}$$
(4.2.2)

Resistors R1 and R2 are used for the biasing of the transistor and capacitors C3 and C4 are used for blocking direct current. The inductor L2 is used as a radio-frequency choke. Chokes in electronics are used as high-frequency alternating current blockers. This choke in this case is used to help to start the oscillation it will block the frequency of oscillation but will pass through the direct current.

The L on Figure 4.2.1 symbolizes the upper coil shown in Figure 4.1.1. Since it is in a form of solenoid the value of inductance can be calculated by equation (4.2.3)[31]. From it, it is possible to see that inductance is dependant on the diameter of coil and number of turns.

$$L = \frac{\mu N^2 A}{l} \tag{4.2.3}$$

Where L – Inductance (H)

  μ – Magnetic permeability of the environment (N A^{-2})

  A – Cross-sectional area (mm^2)

  N – Number of turns
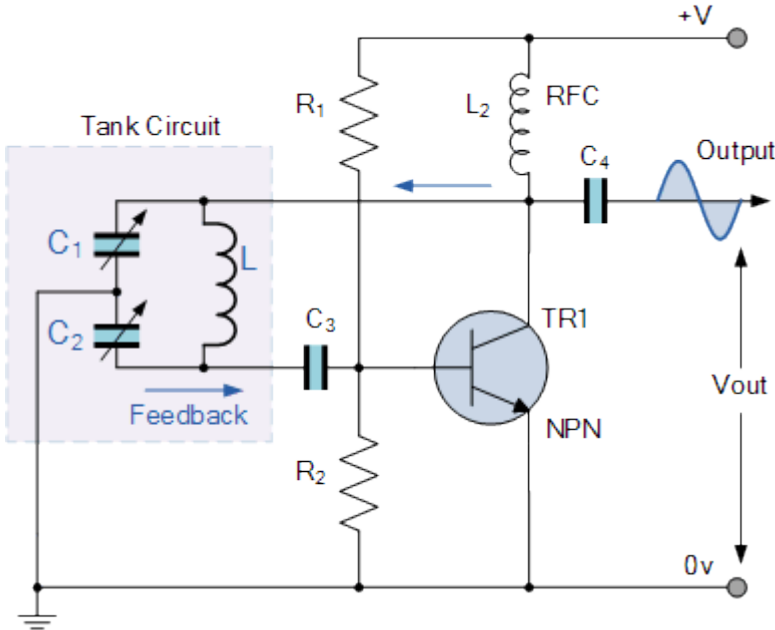
  L – Length of the solenoid (mm)

Figure 4.2.1 – Colpitts oscillator basic schema

The efficiency of the coupling is defined by the Q-factor of transmitter coil. It can be calculated by equation (4.2.4) [29][13]. From that we can say that the larger inductance the better efficiency. That means that the more diameter and more turns the transmitter coil has,

the higher efficiency. Also it is important that coil should have as much turns per length unit as possible.

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} \qquad\qquad (4.2.4)$$

Where R – Resistance (Ω)

There are multiple simpler designs availible, if the smaller efficiency is needed, then some of those designs can be used. Depending on the maximum distance of the levitation even non-resonant technologies can be used. One such project was found on instructables website. The project uses non-resonant inductive coupling. The project produced around 2-3cm distance. The given circuit is show in Figure 4.2.2. For example in case of the levitational prototype created during this project, this distance would be sufficient. It is important to note, that the diameter of the coils must be the same in case of this project. Before deciding on the method, it is important to know the distance over which the energy must be transmitted. Even when using the resonant inductive transfer, because the parameters of the transmitter and receiver circuits will differ. On bigger distances bigger coil diameters are needed, higher frequency of the oscillation is needed etc.
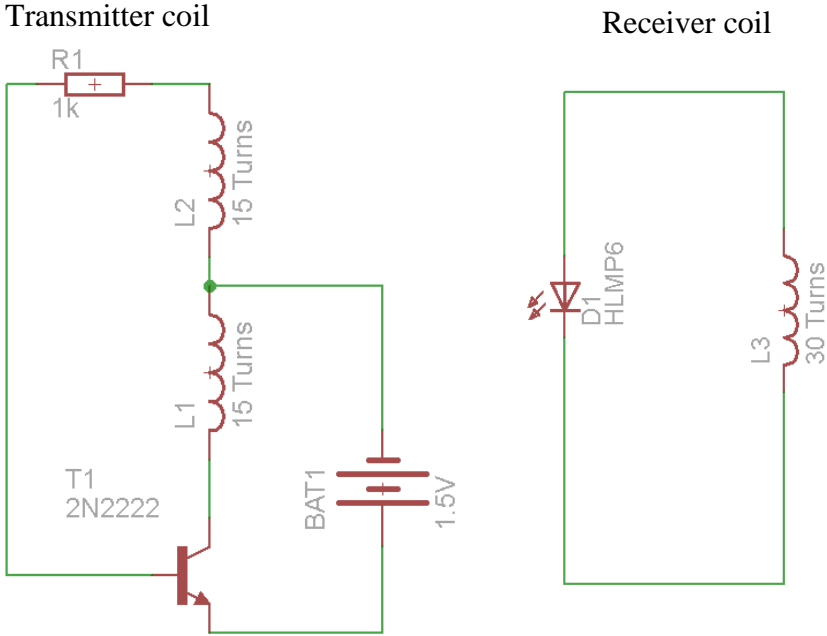
Figure 4.2.2 – Non-resonant project [33]

Example of working inductive resonant coupling has also been found. The basic schematic given by the author is shown on Figure 4.2.3 [34]. The results of this project are more than enough for the current project. The distance of 6 to 10 cm was achieved. However the problem lies in the dimensions of the coils. The diameter is too big to fit ine the lightbulb.
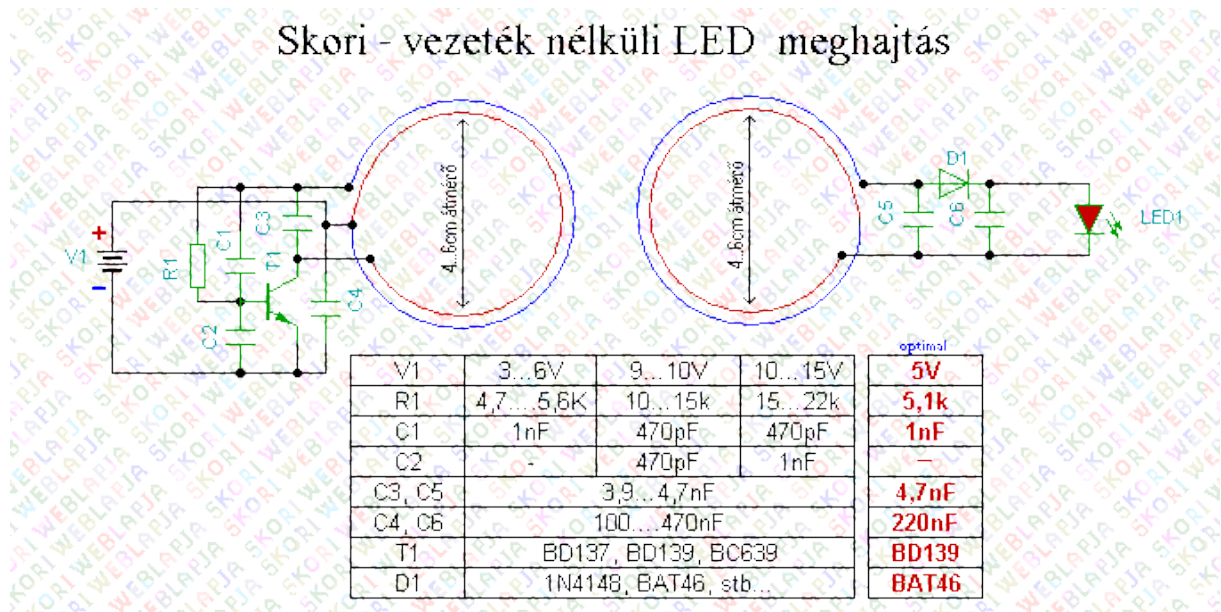
Figure 4.2.3 – Resonant inductive coupling example project

4.3 Receiver coil

In case of Colpitts circuit the transmitter schematic for receiving the energy is simple. It is a basic RLC schema, it is shown on Figure 4.3.1.
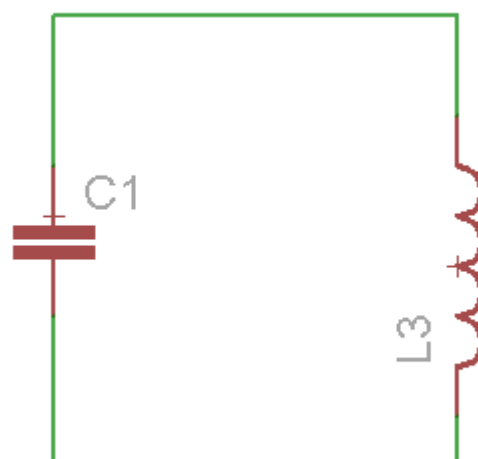
Figure 4.3.1 – Receiver coil circuit

Frequency of receiver coil can be calculated using equation (4.3.1)[29][13]. Using equation (4.3.1) and 4.2.1 it is possible to calculate the capacitors and inductors for both circuits for one frequency.

$$f = \frac{1}{2\pi\sqrt{LC}}$$ (4.3.1)

Where f – Frequency of oscillation (Hz)

L – Inductance (H)

C – Capacitance (F)

It is possible to add rectifier to the receiver coil and voltage regulator, but the need for that depends largerly on the working range. If the voltage will be too high the LED's will burn down.

4.4 **Combining both technologies**

The complete project schema can be seen on Figure 4.4.1. It should be noted that it is not the design of the product, because that would need a work of the designer. As before the secondary coil and permanent magnets will be placed inside the lightbulb.
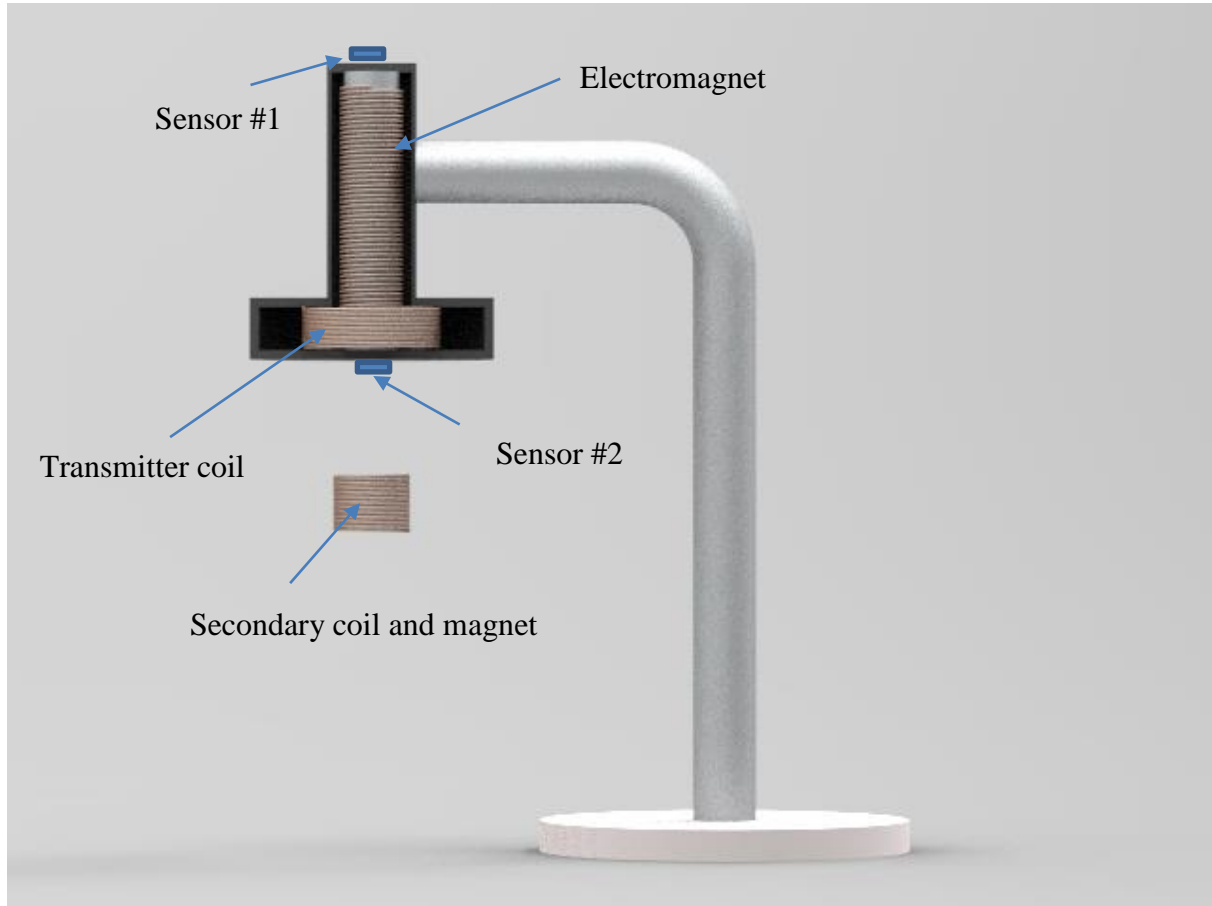
Figure 4.4.1 - Basic scheme of the project

The reason why both of the technologies can coexist and not harm each other is that changing magnetic field is driving receiver coil. Magnetic field is changing due to current oscillations inside the circuit. Oscillations of the magnetic field used for levitations are really small compared to the transmitter coil magnetic field oscillations. Magnetic field used for levitation is trying to stay at a single value oscillating slightly.

5 CONSTRUCTION

5.1 Building materials

There are multiple paths to choose when choosing materials, it is important to bear in mind that not only efficiency and good qualities of the materials but also the cost and availibility. The lightbulb and the base will be discussed separately.

5.2 Problems in current schema

The problem with the setup shown in Figure 4.4.1 is that if the operation of the system is suddenly stopped, for example electricity supply is cut off, the lightbulb will fall down. This can result in the damaged lightbulb. This problem has two steps of solving.

First step is to make the lighbulb as light as possible and the material must be fairly strong. Ordinary glass material that is used frequently in lightbulbs is not suitable. Also the metal cap at the base can be substituted with other material like plastic.

One of the possible solutions is to replace glass material with acrylic. The impact strength is higher than that of a glass, it can be compared to the impact strength of a tempered glass and it does not shatter. Also it should be noted that the acrylic material is lighter than glass. It is also easier to process.[35][36]

Second step is to prevent lightbulb from falling onto rigid surface. There are multiple solutions to that as an example it is possbible to place something soft underneath the lightbulb. Even if there is a system that would prevent lightbulb from falling the lightbulb must be more durable and it must not shatter like glassbulbs, because the levitation system is not as stable as current alternatives.

In order to prevent the lightbulb from falling it is possible to have some backup systems, that would act when the electricity supply gets cut. For example the lightbulb could be brought near the electromagnet, so that the permanent magnets would get attracted to the core and would hold the lightbulb up using the force of attraction to ferromagnetic core. Other alternatives are connected with construction design solutions, like making special parts that would catch the falling lightbulb. There are many options to that, starting from putting cushion below the lightbulb ending with specially designed base. Example of such design can be seen in Figure 5.2.1. Under the lightbulb there is a pit that has cushion inside to make the fall softer.

Figure 5.2.1 - Design example with cushion under lightbulb

5.3 **Lightbulb**

Lightbulb in our case is only decoration, in place of lightblub it is possible to put any other decoration. For example bottle or christmass tree ball. However instead of ordering custom decorations it is possible to order already existing lightbulbs and modify them, that means replace electronic parts inside. Example of such lightbulb can be seen on Figure 5.3.1. This lightbulb is made of plastic and acrylic materials. It is also very light 21g. It also comes with 5 LEDs. The price of such lightbulb is 2.54 euro for one lightbulb. Ofcourse the quality should be checked, but the characteristics right now seem optimal.

Figure 5.3.1 – Example of the lightbulb that can be used[37]

6 HEALTH AND SAFETY

The electromagnetic waves are considered to be dangerous by many people, but in reality there are a lot of conditions and criteria, when they can be considered dangerous or harmful in any way. Magnetic fields themselves are not harmful to human health or at least no evidence presently exists to support that. The problems begin, when magnetic fields start oscillating at high frequencies, this induces electric fields. Electric fields are harmful to the human body. However magnetic fields oscillating on radio frequencies have no evidence to be harmful to human body. In case of this project the energy transfer is done on radio frequencies.

There are some claims that radio wave frequencies may be the reason to the increase in cancer diseases. However this is the consequence of misinterpretation of Worl Organization Study. Their study simply shows that there may be connection, but it is said that amount of statistical data and information is not enough to reach any conclusions.[39]

At high frequencies (between 100KHz and 300GHz) the increase of heat in exposed tissues. The lower frequency penetrates deeper. Body can accumulate such heat, but the heat gets dissipated by the internal temperature regulation process. However above a threshold value they can provoke serious health effects like burns our heatstroke.[40]

A lot of research was done to investigate long term effects of high frequency fields, like decrease in sleep quality, headaches, etc. To date none such adverse effects were found. However it was found that there is a small effect on brain activity, however biological implications of such effects have not been found.[40]

At lower frequency (1KHz to 100KHz) the fields and currents are generated inside the body and they can interfere with the body's own electric fields. However at low levels those interactions seem unnoticed and have no adverse effects on health. Long-term exposure to 50-60Hz fields might be associated with risk of childhood leukemia. However current evidence does not lead to that conclusion. To date no real research has shown that there is an adverse effect of lower frequency fields.[40]

Static magnetic fields can be harmful to human body through several different mechanisms. In case of levitation system almost static magnetic field is used. Magnetic fields exert force on moving electrical charges. Cells and particles in the blood will be affected by the fields. However no adverse effects were found when the field strength is below 8 Tesla.[40] The

field generated in case of this project is below 1T and the field of permanent magnet is a little above 1T.

So following that information, there is no health risks associated with the fields that are generated during this project, both levitation and wireless energy transfer technologies are safe.

7 CONCLUSION

In this work firstly availible technologies were analized and the most suitable ones were picked. For levitation system the electromagnetic suspenson system was picked and it was narrowed to electromagnetic attraction. For object position sensing the hall-effect sensors were picked, it should be noted that the system of 2 hall-effect sensors was picked. One sensor goes on top of the electromagnet and the second sensor goes below the electromagnet. For wireless energy transfer the inductive coupling was picked. Depending on the required distance of the object from electromagnet the resonant inductive coupling may be used.

Secondly the levitation system was analyzed. The basic principle of the levitation system is that there is a sensing system that senses how much distance between an electromagnet and the object there is. This information is fed into microcontroller, which decides the strength of the field of the electromagnet. So the position of the lightbulb is controlled by the strength of the magnetic field of the electromagnet.

Although during this work a lot of mathematics and related work were examined, the interaction between electromagnet and magnet is complex. No methods for such calculations were found and further research would have led to a different thesis topic. That is why the electromagnet was picked based on experimentation process. In this work 3 electromagnets were made.

All the electronic components for the control scheme were picked and the scheme was drawn. The electronic scheme can be seen in Appendix 6 and the prototype electronic scheme is in Appendix 5. Also different approaches to the control were discussed.

The basic control program has been written and tested. The working algorithm is PID control algorithm. Ways to make the algorithm better were discussed, however the ability of this algorithm to hold up the magnet with weight was found to be sufficient. A big problem of current solution is the complexity of tuning, however different methods were presented to solve that problem. While experimenting with prototype it became apparent that the standard commands of the Arduino library were not sufficient, the system was not responding fast enough. Ways to solve that were explored and the solution was found.

Thirdly the wireless energy transfer system was analyzed and developed. The basic idea is that there is a transmitter coil and a receiver coil. Different ways were explained and some circuits of existing projects were shown. Basic idea and circuit was developed. The

transmitter circuit is an oscillating circuit, that by oscillating generates magnetic field that induces electricity in reciever coil. The reciever is inductor-capacitor circuit that when revieves electricity starts oscillationg. The oscillation frequencies should be tuned to be the same.

During the proccess some example designs were created, however no concrete construction was made, because that depends on the final design of the project, which was not decided. However main requirements for the contstruction were decided. The flaws of the project were analyzed and solutions to them were found.

The health and safety part of the magnetic fields is a big concern for many people and there circulate a lot of different ideas. Main concerns were discussed and materials published by big organizations that research this matter were analyzed. It became apparent, that the strength of the fields and their oscillation frequency is not high enough to harm of negatevily affect human body in any way.

In order to start production of this project there still is a lot of work to be done, the concrete characteristics must be chosen and the design has to be developed. Main work is the tuning of the levitation program and the ciruits of the wireless transfer system.

There are multiple things that can be done in order to make the project better. Big step further would be to change the control program to be able to answer to outer disturbances. The system right now is stable, but it is too vurnerable to outside disturbances. Implementing control of the lightbulb brightness, designing the system that would react to supply being cut off would greatly benefit the project.

The levitating lightbulbs have almost no benefits compared to standard lightbulbs. They consume more electricity, they are less stable, they are more expensive and can fall if the electricity supply is cut off. There can be some special circumstances when this can be applied, for example some design solutions may require that there are no holes where the lightbulb could be connected to the supply. The main use of levitating lightbulbs would be entertainment, it could be used in shops or some restaurants to impress people. Also these bulbs are only the start, similar idea can be used on many things. Almost everything can be made to levitate. This would solve some major problems of friction and vibration. For example Crealev company already has made levitating keyboard.

To make a conclusion to this work, it could be said that the set requirements were met. Main existing methods of implementation of used technologies were analyzed and most suitable were chosen. Despite resorting to experimental methods, that are less preoritized the system design requirements and guidelines were outlined. Construction design example were made and basic requirements were set. The safety of the design was analyzed. All of the chosen methods have working examples and can be implemented fairly easily once all of the characteristics are picked and tuned.

KOKKUVÕTE

Selles töös esimesena analüüsiti olemasolevaid tehnoloogiaid ja valiti kõige sobilikumad antu töö jaoks. Levitatsiooni süsteemi jaoks valik jäi elektromagneetilisel hõljumisel, täpsemalt elektromagneetilisel tõmbel. Objekti positsiooni mõõtmiseks kasutatakse hall-effekti sensorid ja süsteem koosneb kahest sensorist. Üks sensror läheb elektromagneti peale ja teine sensor elektromagneti alla. Juhtmeta energia transpordiks kasutatakse induktiivset ühendust. Sõltuvalt vajalikust distantsist objekti ja elektromagneti vahel, resonantne induktiivne ühendus võib olla võetud kasutusele.

Teisena oli levitatsiooni süsteem analüüsitud. Selline süsteem seisneb selles, et sensorite süsteem mõõdab kaugust elektromagneti ja objekti vahel, annab see informatsioon edasi mikrokontrollerisse, mis omakorda otsustab kui tugev väli elektromagnetil peab olema. Seega pirni positsioon kontrollitakse elektromagneti magnetvälja tugevuse abil.

Kuigi selle töö jooksul on analüüsitud palju matemaatilisi ja seotud töid, magneti ja elektromagneti vaheline vastasmõju on keeruline. Ei leitud meetodeid selle arvutamiseks ja edasine uuring oleks viinud teisele diplomi teemale. Selle tõttu elektromagneti valik on tehtud eksperimentaalselt. Selle töö jooksul on tehtud 3 elektromagnetit.

Kõik elektroonilised komponendid kontrollskeemi jaoks on valitud ja skeem joonistatud. Elektroonilist skeemi on võimalik näha Lisas 6 ja prototüübi elektrooniline skeem on Lisas 5. Samuti erinevad võimalused kontrolliks on arutatud.

Baas kontrollprogramm on kirjutatud ja testitud. Töötav algoritm on PID kontrolleri algoritm. Algoritmi parandamise meetodid on arutatud, kuid antud algoritmi töö on leitud piisavaks. Üheks probleemiks antud variandi puhul on selle häälestuse keerukus, kuid selle lihtsustamiseks on toodud välja erinevad meetodid. Prototüübi ekperimentide käigus selgus, et süsteem ei reageerinud piisavalt kiiresti. Selle probleemi lahendusi on uuritud ja lahendus leitud.

Kolmandana juhtmeta energia ülekanne süsteem analüüsiti ja arendati. Idee seisneb selles, et on olemas kaks pooli, üks on saatja ja teine vastuvõtja. Erinevad võimalused on selgitatud ja erinevad töötavad süsteemid on näidatud. Idee ja skeem on töödatud välja. Saatja pool on ostsilaatorskeem, mis võnkumise tulemusena tekitab magnetvälja, mis indutseerib elektri vastuvõtja poolis. Vastuvõtja skeem on induktor-kondensaator skeem, mis hakkab võnkuma kui võtab vastu elektrit. Võnkumisesagedused peavad olema tuunitud üheks saguseks.

Mõned konstruktsiooni disainid on töötatud välja, kuid lõplikud konstruktsiooni tehtud ei ole, kuna see sõltub suuremas osas disainist, mis pole töötatud välja. Kuid peamised nõuded ja reeglid on töötatud välja. Töö nõrkused on analüüsitud ja võimalikud lahendused on leitud.

Ohutus magnetväljade puhul tekitab suurt muret paljudes inimestes ja on olemas palju arvamusi selle kohaselt. Peamised mured on toodud välja ja arutatud, materjalid, mis on suurte organisatsioonide poolt, kes antud probleemi uurivad, avaldatud, on analüüsitud. Selle tulemusena, tuli välja, et antud töös kasutatud magnetväljade tugevus ja võnkumise sagedus ei ole piisavalt suur, et tekitada mingit kahju või negatiivselt mõjutada inimese keha.

Selleks, et alustada antud töö produkti tootmist, on vaja veel teha palju tööd, valida konkreetsed karakteristikud ja disaini arendada. Peamine töö on seotud levitatsiooni programmi ja juhtmeta energia edastamise skeemide häälestamisega.

On olemas mitu võimalust teha antud töö paremaks. Üheks suureks sammuks edasi oleks kontrollprogrammi muutmiseks, et ta oleks suuteline väljaspoolt tulnud häiretele reageerima. Süsteem hetkel on stabiilne, kuid ta on liiga nõrk väljaspoolt tulnud häirete vastu. Teiseks, kontrollsüsteemile lisamine lambi heleduse reguleerimise võimalus. Samuti süsteemi arendamine elektritoide häiretele (elektritoide ebastabiilne toide või toide lõpp) reageerimiseks oleks antud proektile kasulik.

Hõljuvad lambid ei oma peaaegu mingeid eeliseid võrreldes tavaliste lampidega. Nad tarbivad rohkem elektrit, nad on vähem stabiilsed, nad maksavad rohkem ja võivad kukkuda, elektritoide häire puhul. Sellel süsteemil on mõned erilised kasutused, kus tavaliseid lampe ei saa kasutada, näiteks seda projekti saab kasutada, kui lambi toitmiseks ei ole võimalik puurida auke juhtmete jaoks. Kõige suurem kasutuse ala sellel süsteemil saab olema meelelahutus, ta võib olla kasutusel poodides ja restoraanides, inimestele muljet jätmiseks. Samuti antud projekt on ainult algus, sarnased ideed saavad kasutuse erinevates väljades. Peaaegu kõike saab leviteerida. See võib aidata mõnede probleemide, mis on seotud vibratsiooniga ja hõõrumisega, lahendamiseks. Näiteks Crealev on juba loonud hõljuva klaviatuuri.

Kokkuvõteks saab öelda, et töös seatud eesmärgid on täidetud. Peamised olemasolevad tehnoloogiad on analüüsitud ja kõige sobivamad on valitud. Kuigi kasutati eksperimentaalseid meetodeid, mis on vähem prioriteedis, süsteemi disaini nõuded ja juhtnöörid on kirjeldatud. Konstruktsiooni disaini näidis on tehtud ja peamised nõuded on seatud. Antud süsteemi

ohutus on analüüsitud. Kõik valitud meetodid omavad töötavaid näiteid ja nende rakendamine on lihtne, kui kõik karakteristikud on valitud ja häälestatud.

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APPENDICES

Appendix 1

int transistor = 3;//Pin that controls transistor

int CV=0;///Current value

float val = 0;//Output value

int sensor = 0;//Sensor value

int sensor2 = 0;//Sensor value

int SetP = 350;//setpoint

int pot = 0;//Additional component equilibrium position, controlled by variable resistor

float PGain = 2;//Kp

float DGain = 20.1;//Kd

float IGain = 0.001;//Ki

int pE=0; int dE=0; int iE=0;//Calculated error components

int LV=SetP;//Last error value

#define FASTADC 1 //Define FASTADC constant as 1


```
// defines for setting and clearing register bits
#ifndef cbi
#define cbi(sfr, bit) (_SFR_BYTE(sfr) &= ~_BV(bit))
#endif
#ifndef sbi
#define sbi(sfr, bit) (_SFR_BYTE(sfr) |= _BV(bit))
#endif
signed long ms=millis();
int mode = 0;
int readInt=0;
void setup()
{
  #if FASTADC
// set prescale to 16 16 MHz / 16 = 1 MHz
 sbi(ADCSRA,ADPS2) ;
 cbi(ADCSRA,ADPS1) ;
```

```
 cbi(ADCSRA,ADPS0) ;
 #endif
// Serial.begin(9600);
// Setup the timer 2 as Phase Correct PWM, 3921 Hz.
 pinMode(3, OUTPUT);
 pinMode(11, OUTPUT);
// Timer 2 register: WGM20 sets PWM phase correct mode, COM2x1 sets the PWM out to
channels A and B.
 TCCR2A = 0;
 TCCR2A = _BV(COM2A1) | _BV(COM2B1) | _BV(WGM20);
// Set the prescaler to 8, the PWM freq is 16MHz/255/2/<prescaler>
 TCCR2B = 0;
 TCCR2B = _BV(CS21);
 Serial.begin(115200);
}
void processCommand( int cmd )
{
  char tmp[64];

  switch(cmd)
  {
   //Serial communication commands
    case 'p':
      Serial.println("Mode: PGain");
      mode=1;
     // PGain -= P_INCR;
      if( PGain < 0 ) PGain = 0;
      break;
    case 'P':
      mode=1;
      Serial.println("Mode: PGain");
     // PGain += P_INCR;
      break;
    case 'd':
```

```
      mode=2;
      Serial.println("Mode: DGain");
    // DGain -= D_INCR;
      if( DGain < 0 ) DGain = 0;
      break;
  case 'D':
      mode=2;
      Serial.println("Mode: DGain");
    // DGain += D_INCR;
      break;
  case 'i':
      mode=3;
      Serial.println("Mode: IGain");
    // IGain -= I_INCR;
      if( IGain < 0 ) IGain = 0;
      break;
  case 'I':
      mode=3;
      Serial.println("Mode: IGain");
    // IGain += I_INCR;
      break;
  case 's':
      mode=4;
      Serial.println("Mode: SetP");
    //SetP --;
      break;
  case 'S':
      mode=4;
      Serial.println("Mode: SetP");
    //SetP ++;
      break;
  case 'x':
  case 'X':
```

```
        sprintf(tmp, "s(%d) c(%d) h(%d) P(%u, %d) D(%u, %d) I(%u,%d) sensor:%d\n", SetP,
(int)val,      CV,      (uint16_t)(PGain*1000.0),      pE,      (uint16_t)(DGain*1000.0),      dE,
(uint16_t)(IGain*1000.0), iE, sensor);
        Serial.print(tmp);
        break;
      default:
        readInt = readInt*10;
        readInt=readInt-48+(int)cmd;
        if(mode==1){
          PGain=(float)readInt/1000;
        }
        else if(mode==2){
          DGain=(float)readInt/1000;
        }
        else if(mode==3){
          IGain=(float)readInt/1000;
        }
        else if(mode==4){
          SetP=(float)readInt;
        }
        break;
    }
}
void loop()
{
  if( (signed long)( millis() - ms ) >= 0){//ensure that 1 ms has passed
    readInt=0;
    while( Serial.available() ){
      int byteOne = Serial.read();
      processCommand( byteOne );
    }
    ms=ms+1;
    sensor=analogRead(A0);
    sensor2=analogRead(A1);
```

```
pot = map(analogRead(A5), 0, 1024, 0, 255);//getting value from potentiometer
CV=abs(sensor-sensor2);//object position calculation
pE = (SetP-CV);//p component calculation
dE = (LV-pE);//d component calculation
iE = iE + pE; //i component calculaion
iE=constrain(iE, -255, 255);
val=pot + (int)PGain*pE + (int)DGain*dE + iE*(int)IGain;//PID output
val = constrain(val, 0, 255);
val = map(val, 255, 0, 0, 255);
OCR2B = val;//value pwm output to electromagnet
LV = pE;
}
}
```

Appendix 2

Absolute Maximum Ratings

Stresses exceeding the absolute maximum ratings may damage the device. The device may not function or be operable above the recommended operating conditions and stressing the parts to these levels is not recommended. In addition, extended exposure to stresses above the recommended operating conditions may affect device reliability. The absolute maximum ratings are stress ratings only. Values are at T_C = 25°C unless otherwise noted.

Symbol	Parameter		Value	Unit
V_{CBO}	Collector-Base Voltage	TIP120	60	V
		TIP121	80	
		TIP122	100	
V_{CEO}	Collector-Emitter Voltage	TIP120	60	V
		TIP121	80	
		TIP122	100	
V_{EBO}	Emitter-Base Voltage		5	V
I_C	Collector Current (DC)		5	A
I_{CP}	Collector Current (Pulse)		8	A
I_B	Base Current (DC)		120	mA
T_J	Junction Temperature		150	°C
T_{STG}	Storage Temperature Range		-65 to 150	°C

Thermal Characteristics

Values are at T_C = 25°C unless otherwise noted.

Symbol	Parameter	Value	Unit
P_C	Collector Dissipation (T_A = 25°C)	2	W
	Collector Dissipation (T_C = 25°C)	65	

Electrical Characteristics

Values are at T_C = 25°C unless otherwise noted.

Symbol	Parameter		Conditions	Min.	Max.	Unit
V_{CEO}(sus)	Collector-Emitter Sustaining Voltage	TIP120	I_C = 100 mA, I_B = 0	60		V
		TIP121		80		
		TIP122		100		
I_{CEO}	Collector Cut-Off Current	TIP120	V_{CE} = 30 V, I_B = 0		0.5	mA
		TIP121	V_{CE} = 40 V, I_B = 0		0.5	
		TIP122	V_{CE} = 50 V, I_B = 0		0.5	
I_{CBO}	Collector Cut-Off Current	TIP120	V_{CB} = 60 V, I_E = 0		0.2	mA
		TIP121	V_{CB} = 80 V, I_E = 0		0.2	
		TIP122	V_{CB} = 100 V, I_E = 0		0.2	
I_{EBO}	Emitter Cut-Off Current		V_{EB} = 5 V, I_C = 0		2	mA
h_{FE}	DC Current Gain[1]		V_{CE} = 3 V, I_C = 0.5 A	1000		
			V_{CE} = 3 V, I_C = 3 A	1000		
V_{CE}(sat)	Collector-Emitter Saturation Voltage[1]		I_C = 3 A, I_B = 12 mA		2.0	V
			I_C = 5 A, I_B = 20 mA		4.0	
V_{BE}(on)	Base-Emitter On Voltage[1]		V_{CE} = 3 V, I_C = 3 A		2.5	V
C_{ob}	Output Capacitance		V_{CB} = 10 V, I_E = 0, f = 0.1 MHz		200	pF

Note:

1. Pulse test: pw ≤ 300 µs, duty cycle ≤ 2%.
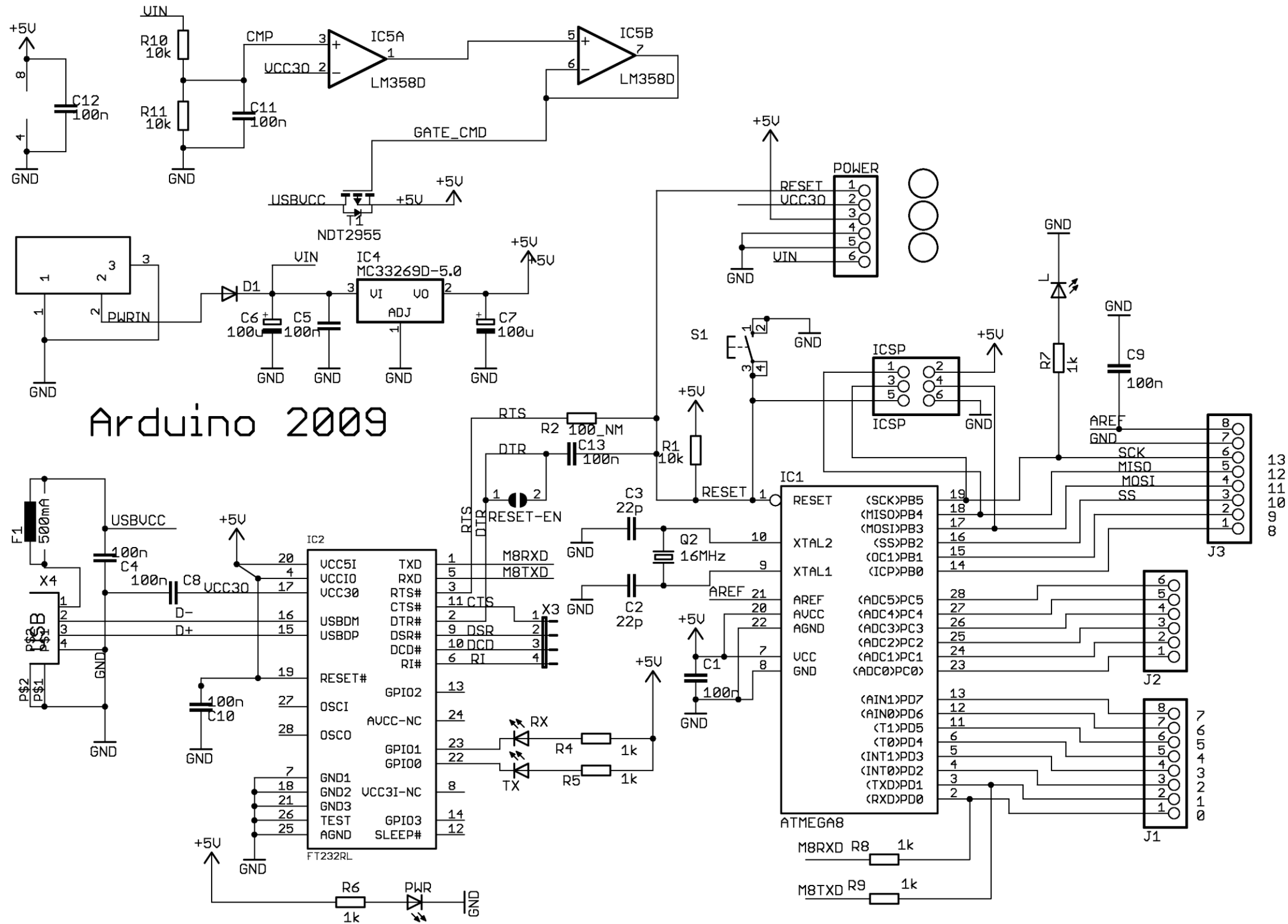
Arduino 2009

Appendix 4

Electrical Characteristics (LM7805)

Refer to the test circuit, -40°C < T_J < 125°C, I_O = 500 mA, V_I = 10 V, C_I = 0.1 μF, unless otherwise specified.

| Symbol	Parameter	Conditions		Min.	Typ.	Max.	Unit
V_O	Output Voltage	T_J = +25°C		4.80	5.00	5.20	V
		I_O = 5 mA to 1 A, $P_O \le$ 15 W, V_I = 7 V to 20 V		4.75	5.00	5.25	
Regline	Line Regulation[2]	T_J = +25°C	V_I = 7 V to 25 V		4.0	100.0	mV
			V_I = 8 V to 12 V		1.6	50.0	
Regload	Load Regulation[2]	T_J = +25°C	I_O = 5 mA to 1.5 A		9.0	100.0	mV
			I_O = 250 mA to 750 mA		4.0	50.0	
I_Q	Quiescent Current	T_J = +25°C			5	8	mA
ΔI_Q	Quiescent Current Change	I_O = 5 mA to 1 A			0.03	0.50	mA
		V_I = 7 V to 25 V			0.30	1.30	
$\Delta V_O / \Delta T$	Output Voltage Drift[3]	I_O = 5 mA			-0.8		mV/°C
V_N	Output Noise Voltage	f = 10 Hz to 100 kHz, T_A = +25°C			42		μV
RR	Ripple Rejection[3]	f = 120 Hz, V_I = 8 V to 18 V		62	73		dB
V_{DROP}	Dropout Voltage	T_J = +25°C, I_O = 1 A			2		V
R_O	Output Resistance[3]	f = 1 kHz			15		mΩ
I_{SC}	Short-Circuit Current	T_J = +25°C, V_I = 35 V			230		mA
I_{PK}	Peak Current[3]	T_J = +25°C			2.2		A

Notes:

2. Load and line regulation are specified at constant junction temperature. Changes in V_O due to heating effects must be taken into account separately. Pulse testing with low duty is used.
3. These parameters, although guaranteed, are not 100% tested in production.

Absolute Maximum Ratings

Stresses exceeding the absolute maximum ratings may damage the device. The device may not function or be operable above the recommended operating conditions and stressing the parts to these levels is not recommended. In addition, extended exposure to stresses above the recommended operating conditions may affect device reliability. The absolute maximum ratings are stress ratings only. Values are at T_A = 25°C unless otherwise noted.

Symbol	Parameter		Value	Unit
V_I	Input Voltage	V_O = 5 V to 18 V	35	V
		V_O = 24 V	40	
$R_{\theta JC}$	Thermal Resistance, Junction-Case (TO-220)		5	°C/W
$R_{\theta JA}$	Thermal Resistance, Junction-Air (TO-220)		65	°C/W
T_{OPR}	Operating Temperature Range	LM78xx	-40 to +125	°C
		LM78xxA	0 to +125	
T_{STG}	Storage Temperature Range		- 65 to +150	°C

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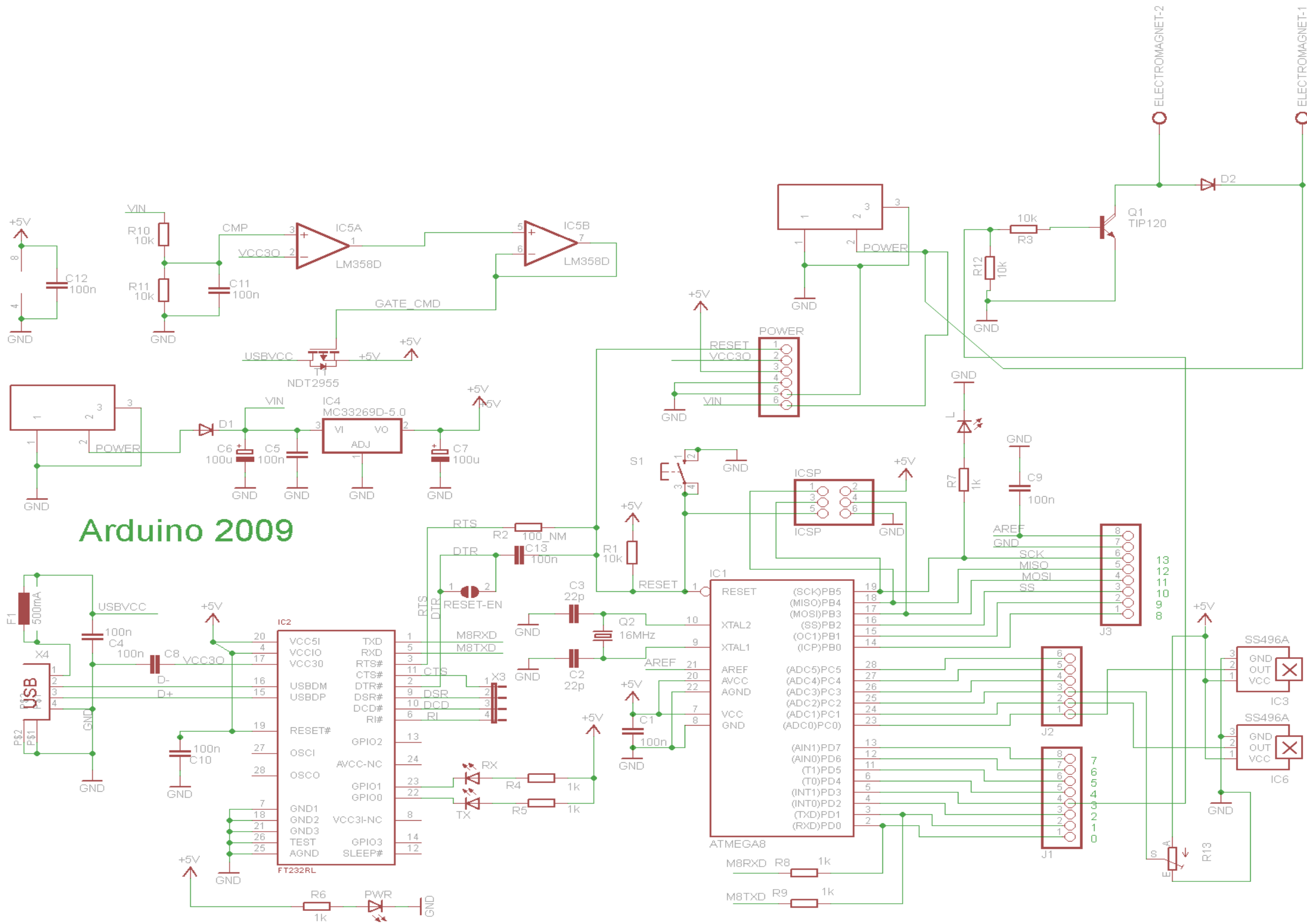
Appendix 6
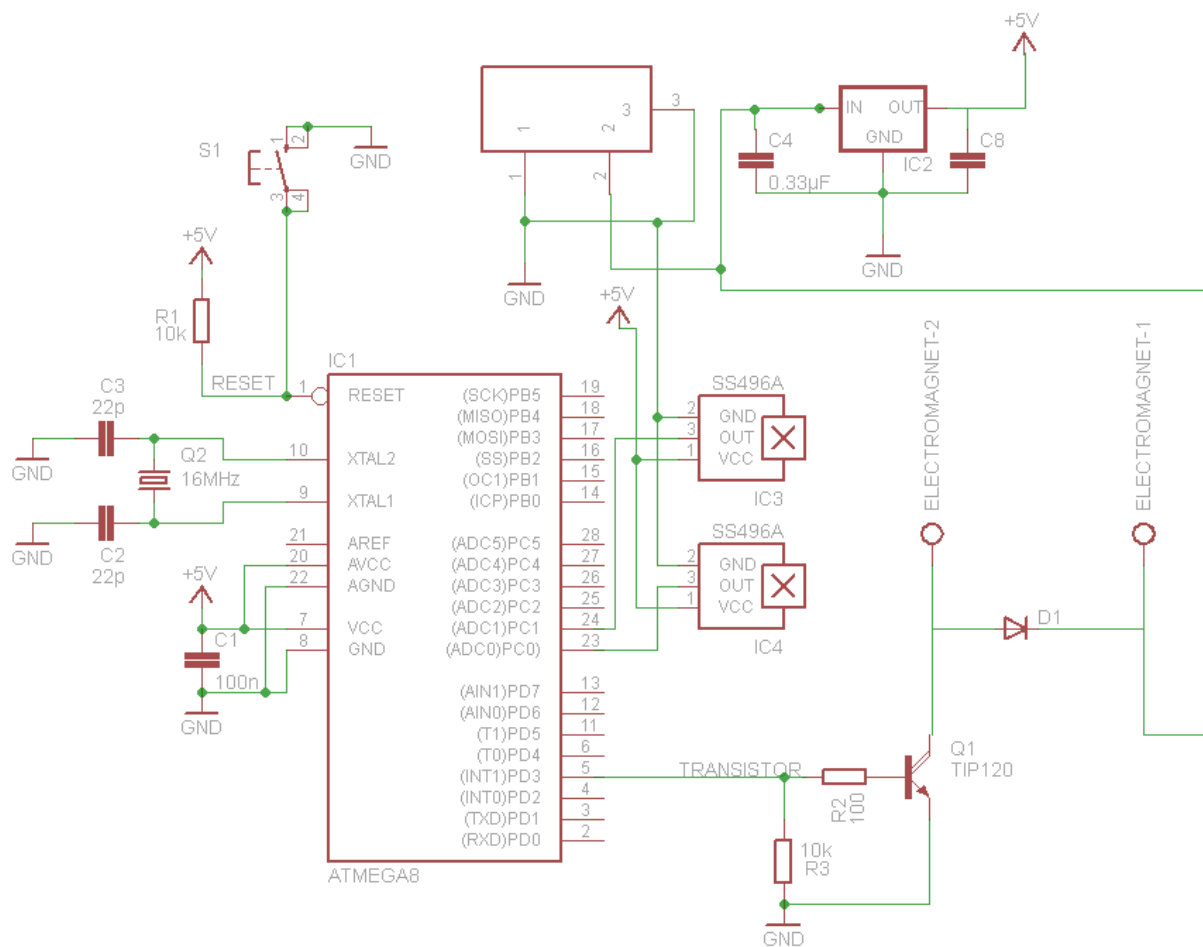
Part	Name	Marking	Quantity
IC1	ATMEL 8-Bit Microcontroller	Atmega328P	1
IC2	Positive voltage regulator	LM7805	1
IC3, IC4	Hall-effect sensor	SS496A	2
D1	Diode 2A		1
R1, R3	Resistor 10K Ohm		2
R2	Resistor 100 Ohm		1
Q1	NPN Darlington Transistor	TIP120	1
Q2	16MHz Crystal Oscillator		1
S1	Push-button		1
C1	Ceramic disk capacitor 0.1uF		1

C2, C3	Ceramic disk capacitors 22pF		2
C4	Electrolytic capacitor 0.33uF		1
C5	Electrolytic capacitor 0.1uF		1