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Artjom Terestsenko

Magnet levitatsiooni süsteemi prototüübi projekteerimine ja arendamine

MSc Lõputöö

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Design and development of laboratory prototype magnetic levitation system

MSc Final Work

Author applies for degree of Master of Technical Sciences (M.Sc.)

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AUTHOR'S DECLARATION

I declare that I have written this graduation thesis independently.

These materials have not been submitted for any academic degree.

All the works of other authors used in this thesis have been referenced.

The thesis was completed under supervision
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Author

..... signature

The thesis complies with the requirements for graduation theses.

“.....”201...a.

Supervisor

..... signature

Accepted for defence.

..... chairman of the defence committee

“.....”201... a.

..... signature

MASTER'S THESIS TASK

Year 2016 Springsemester

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Spetsiality: Mechatronics

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MASTER'S THESIS TOPIC:

(in English)Design and development of laboratory prototype magnetic levitation system

(in Estonian)Magnet levitatsiooni süsteemi prototüübi projekteerimine ja arendamine

Assignments to be completed and the schedule for their completion:

Nr	Description of the assignment	Completion date
1.	Overview of the magnetic levitation systems. Formulating requirements to the system being designed and stand. Making first concept. Definition of technical parameters of system and stand being designed.	01.02.2016
2.	Stabilisation methods of magnetic levitation systems. Analysis of advantages and disadvantages of stabilisation methods of magnetic levitation systems. Design of prototypes with different stabilisation systems using MATLAB, Arduino Software.	01.03.2016
3.	Cost calculation of developed systems and stand.	30.04.2016
4.	Printing and binding of Master's thesis.	15.05.2016

Engineering and economic problems to be solved: In this Master's thesis the magnetic levitation systems with different stabilisation methods should be designed and developed. The system allows to analyse all problems of system's control, identification, synthesis of control laws and their realisation. The systems designed will be used in study stand. The aim is to design more cheaper study stand than available in the market. The project cost calculations should be done.

Additional comments and requirements:

Language of the thesis: English

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Deadline for submitting the thesis 16.05.2016

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Supervisor Alina Sivitski /signature/ date 26.02.2016

Confidentiality requirements and other corporate terms and conditions shall be set out on the reverse side.

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Eessõna

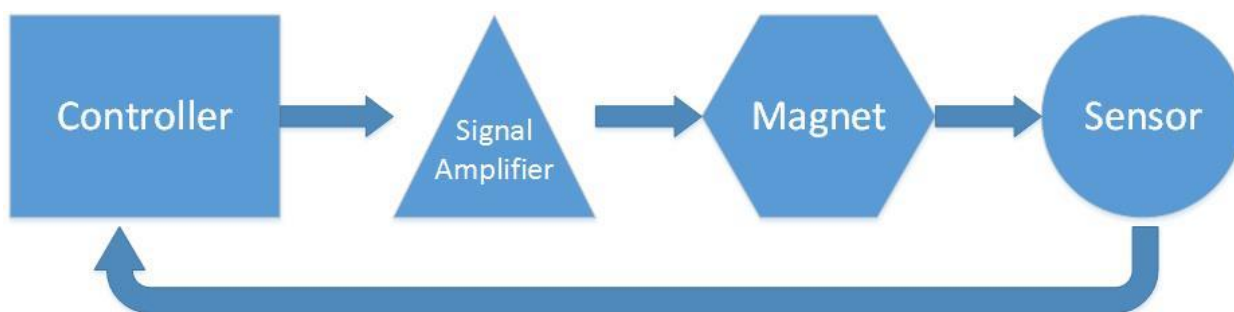
Peamine eesmärk on määrata kindlaks kõige tõhusam algoritmi kontroll. Selleks, et seda teha tuleb luua prototüüp vajalikud eeksperimentide jaoks. Praktiline rakendus võimaldab täielikult uurida iga võimalust. Töö käigus kasutan järgnevaid:

- plaat Arduino MEGA 2560 Board järelevalve- ja juhtimine
- MATLAB ja muid rakendusi et luuamatemaatilisemudeli
- LabVIEW kontrollimiseks "Machine Vision"
- Objektide juhtimine
- Stand

Algoritmide juhtimine erineb ainult tagasisidega. See ühendus on võimalik läbiviia järgmiste andurite abil:

- Halliandur
- Lähedusandur
- Fototransistor
- Machinevision

Joonisel 1 on kujutatud plokk skeem algoritmi töö süsteem.



Joonis 1 Algoritm

Lõppkokkuvõttes, esitletakse projekti lõpptoote. Seal kasutatakse kõige efektiivsem algoritmi, samuti stand peavad vastama kõikidele nõuetele:

- Plug&Play
- Stabiilne töö
- Mobiilsus (liikuvus)
- Madal hind

Tulemuseks meie saame toode, mida saab võrrelda Maglev "INTECO" firmaga. Samuti saame hinnata tõhusust seoses selle väärtusega. Üheks eesmärgiks on luua efektiivse ja odava seade. See alus on võimalik kasutada õppevahendina koolides, ülikoolides. Põhieeliseks on selle hind ja lihtne kasutus.

Foreword

The main objective is to find the most effective control algorithm. In order to do that, a prototype for carrying out the required experiments has to be made. Practical application will allow to study every single option in detail. In the course of the research, the following tools will be used:

- ArduinoMEGA 2560 microcontroller board for management and control
- MATLAB and other applications for creating a mathematical model
- LABVIEW for exercising control with the help of "MachineVision"
- Controllable objects
- Stand

Control algorithms only differ in feedback. This type of connection can be established by means of the following sensors:

- Hall sensor
- Distance sensor
- Phototransistor
- MachineVision

The flow chart of the system algorithm is in figure 1.

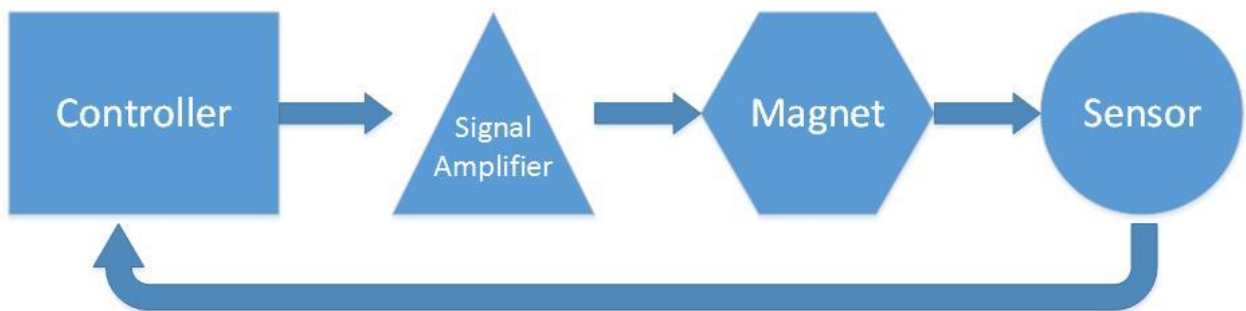


Figure 1 System algorithm

In the end, the project of the final product will be presented. It will use an effective algorithm, and the stand must also conform to relevant requirements:

- Plug & Play
- Stable operation
- Mobility
- Low price

In the result, we will get the product that can be compared with MAGLEV manufactured by *Inteco*. Besides, we will be able to assess its efficacy in relation to its cost. One of the tasks is to develop an efficient and cheap device. This stand can be used as a teaching aid in schools and universities. Its main advantages are its price and user-friendly interface.

Introduction

Magnetic levitation has practical application in many different fields. For example, maglevs, magnetic bearings, and other products. With the help of this technology, it is possible to hold the object in the gravity field by means of magnetic action only. The purpose of this thesis is the stabilization of this system. The topic has been selected at the author's own initiative and includes putting up a stand. This device will help to deal with numerous problems which arise when managing the object in real life. Besides, this device can be used as a teaching aid at schools and universities. This device (figure 2) has already been put up at Tallinn University of Technology.

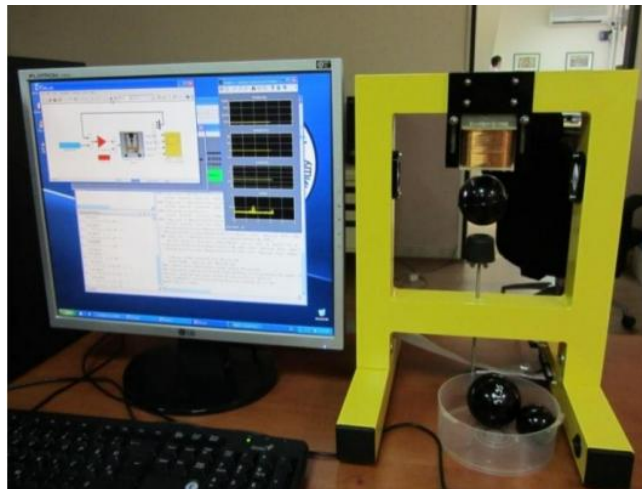


Figure 2 Inteco Maglev System [1]

The manufacturer of this device is the company *Inteco*. It is kept at the Institute of Automation as a demonstrative example of a control system. There can be different control algorithms for a system like that. In this particular case, the control is exercised by means of the MATLAB software. The thesis will first of all focus on the research of several possible control options. After that, the cheapest and the most effective of them will be selected to fit the conditions specified below.

Magnetic levitation system.

In fig. 3, you can see the overview diagram of the system of the magnetic levitation support. Two forces affect a steel ball which is in the air: the force of gravity F_g , which is directed vertically downwards, and the attractive force, F_m , which is generated by the electric magnet when current I flows through it. Hereby x_0 is the distance from the surface of the electric magnet to the ball, I is the current force, V is the voltage applied to the coil, and g is the gravitational constant. The physical parameters present in the system are the specifications of a specific magnetic levitation device: M – ball weight, R – coil resistance, L – coil inductance.

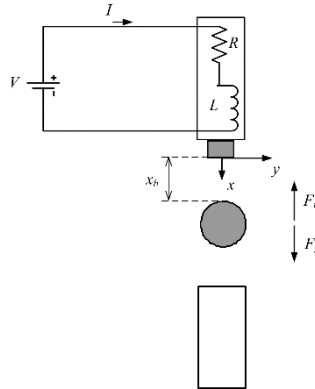


Figure 3 Magnetic levitation system [2]

The model of the process of levitation can be represented in the form of equations [3]:

$$L(z) - \frac{N}{i(t)} \Phi_T = \frac{N^2}{R_T} \quad (1)$$

The main purpose of the system of magnetic levitation is to regulate the voltage on the electric magnet in order to hold the metal object at a pre-set distance from the magnet. If we assume that the whole of the magnetic flux travels through the metal ball, the magnetic induction can be represented by means of the equation 1, where

N is the number of turns of the coil

R_T is magnetic resistance

Φ_T is magnetic flux

If we ignore magnetic resistance, we will come up with equation 2:

$$L(z) = \frac{\mu_0 N^2 A}{2z(t)} \quad (2)$$

The attractive force generated by the magnet is set by the following equation:

$$F(i, z) = -\frac{d}{dz} \left[\frac{1}{2} L(z) i(t)^2 \right] \quad (3)$$

The negation sign in the equation indicates the direction of force. Now, if we insert the equation 2 into the equation 3, we will get the following:

$$F(i, z) = \frac{\mu_0 N^2 A}{4} \left[\frac{i(t)}{z(t)} \right]^2 \quad (4)$$

Thus, in the equilibrium position (i_0, z_0) , the equation will look like this:

$$F_0(i_0, z_0) = \frac{\mu_0 N^2 A}{4} \left[\frac{i_0}{z_0} \right]^2 = mg \quad (5)$$

The dynamics of the electric magnet is determined with the help of the following equation:

$$m\ddot{z}(t) = -F(i, z) + mg = -\frac{\mu_0 N^2 A}{4} \left[\frac{i_0}{z_0} \right]^2 + mg \quad (6)$$

The system dynamics equations are not linear, and, consequently, it is difficult to analyse them. Thus, linearity is achieved in certain points (i_0, z_0) , and after that, the linear model is set by the following equation:

$$\begin{aligned} m\Delta\ddot{z}(t) &= -\frac{\mu_0 N^2 A}{4} \left[\frac{i_0 + \Delta i(t)}{z_0 + \Delta z(t)} \right]^2 + mg = -\frac{\mu_0 N^2 A i_0}{2z_0^2} \Delta i(t) + \frac{\mu_0 N^2 A i_0^2}{2z_0^3} \Delta z(t) \\ &= -K_a \Delta i(t) + K_z \Delta z(t) \quad (7) \end{aligned}$$

Two constants K_z and K_a depend on the current force and the specifications of the object. They will be determined in an experimental way.

After the application of Laplace transformation on both sides of the equation 7, the transfer function will look like this:

$$G_p(s) = \frac{\Delta z(s)}{\Delta i(s)} = -\frac{\left(\frac{K_a}{m}\right)}{\left(s^2 - \frac{K_g}{m}\right)} \quad (8)$$

It should be noted down here that the equations represent the system dynamics in an approximate way, due to the complexity of the description of the electromagnetic field and the availability of additional unaccounted effects exerted by it. Let us point out that major difficulties arise when describing the behaviour of the ball near the surface of the electric magnet.

Then we will determine the parameters and derive the formulas for control system management. The determination of the parameters K_a and K_z is preconditioned by holding the object under the magnet with different gaps. The inductance of the electric magnet is changed depending on the distance between the magnet and the object. The value of inductance is determined by means of the following equation:

$$L(z) = L_c + \frac{L_0 z_0}{z} \quad (9)$$

where L_c is the inductance when the object is absent, and L_0 is the additional inductance generated when the object is present. Now the force equation looks like this:

$$C = \frac{L_0 Z_0}{2} \quad (10)$$

$$F(z) = \frac{i^2}{2} \frac{dL(z)}{dz} = C \left(\frac{i}{z}\right)^2 \quad (11)$$

Based on the equation 7 and formula 10, two constants look like this:

$$K_a = 2c \left(\frac{i_0}{z_0^2}\right) \& K_z = 2c \left(\frac{i_0^2}{z_0^3}\right) \quad (12)$$

Additional inductance (L_0) with the gap of 4 mm (z_0) – (20mH– 18mH)=2mH

We have the following equation:

$$C = \frac{L_0 Z_0}{2} = \frac{2 * 10^{-3} * 4 * 10^{-3}}{2} = 4 * 10^{-6}$$

$$K_a = 2C \left(\frac{i_0}{z_0^2}\right) = \frac{2 * 4 * 10^{-6} * 70 * 10^{-3}}{(4 * 10^{-3})^2} = 0.035(N/A)$$

$$K_z = 2C \left(\frac{i_0^2}{z_0^3}\right) = \frac{2 * 4 * 10^{-6} * (70 * 10^{-3})^2}{(4 * 10^{-3})^3} = 0.6125(N/m)$$

$$G_p(s) = \frac{\Delta z(s)}{\Delta l(s)} = -\frac{\left(\frac{K_a}{m}\right)}{\left(s^2 - \frac{K_z}{m}\right)}$$

The transfer function is defined by the following formula:

$$G_p(s) = \frac{10.5}{(s^2 - 184.3)} \quad (13)$$

Formula 13 shows that the system is unstable. Later on, it will not be possible to stabilize the system by adjusting power output. In order to solve this problem, PD controller must be used. Thus, the transfer function looks like this:

$$GH(s) = G_{pd}(s)G_p(s)K_b = \frac{KK_b(s + z_c)\frac{K_a}{m}}{\left(s^2 - \frac{K_g}{m}\right)} \quad (14)$$

After the substitution of all of the values and carrying out the simulation, the following formula has been generated:

$$GH(s) = \frac{0.0145 * 1000 * 10.54(s + 30.3)}{(s + 13.5)(s - 13.5)} \quad (15)$$

Prototype

Magnet

Table 1 Magnet parameters

Parameters	Values
Number of turns of the coil	1660
Resistance	20 Ω
Induction of the coil	17,6 mH
Diameter of the core	18 mm
Diameter of the wire	0,38 mm
Length of coil	0,06 m

When designing electric magnets, it is desirable to obtain a large power flow. This can be achieved if magnetic resistance is reduced. In order to do that, the magnetic core with the smallest length of the magnetic path and the largest cross section should be selected, and the material with high magnetic conductivity should be used. The magnet was customized. Its resistance is about 20 Ω , and it is optimized for 12 volts. The core has been made from electrical steel and has a cylindrical shape, 16 mm in diameter and 60 mm in length. After studying the magnetization chart, a conclusion has been made that the best possible magnetic induction would be 10,000 – 14,000 Gs. The relevant data has been obtained after studying the so-called hysteresis curve. The hysteresis curve is a curve that shows the dependence of the magnetization on the voltage stress in the external field. The larger the surface of the curve is, the more effort should be made to do reverse magnetization. In figure 4, the curve for electrical steel is depicted.

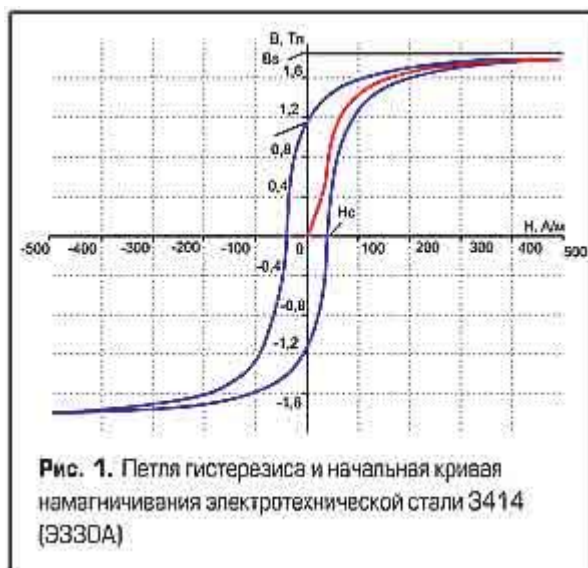


Figure 4 Hysteresis loop [4]

The calculations for the electric magnet that has been obtained are listed below.

$$L = H * \mu_0 \mu_r \quad (16)$$

Where L is the inductance

$$\mu_0 = 4 * \pi * 10^{-7}$$

$$\mu_r = 1$$

$\mu_0 \mu_r$ – magnetic conductivities, H–voltage stress in the magnetic field, from the formula:

$$H = \frac{I * N}{l} \quad (17)$$

Let us combine formulas 16 and 17 to calculate the magnetic induction of the coil:

$$L = \frac{I * N}{l} * \mu_0 * \mu_r = \frac{0,6 * 1660 * 1,257 * 10^{-6}}{0,06} \approx 17,6(mH) \quad (18)$$

o find the maximum weight of the object, the lifting capacity of the magnet must be calculated:

$$F = \frac{(N * I)^2 * \mu_0 * S}{(2 * l_p^2)}$$

Where

F is force

I is current

$l_p=10\text{mm}$ - distance from the object (this distance is sufficient to register levitation)

S is surface area

N is the number of turns of the coil

μ_0 is the magnetic constant

After substituting the values, this is what we get:

$$F = \frac{(1660 * 0,6)^2 * 4 * 3,14 * 10^{-7} * 0,000254}{(2 * 0,001^2)} \approx 1,583(N) \quad (19)$$

Из этого следует, что на расстоянии в 10мм магнит способен удерживать объект массой 150 грамм.

Frame

To make a prototype, firstly, the frame must be made, to which the magnet and other elements will be attached. Dimensions and the general view are presented below (figure 5,6). The structure is very simple, and there is nothing difficult in its construction.

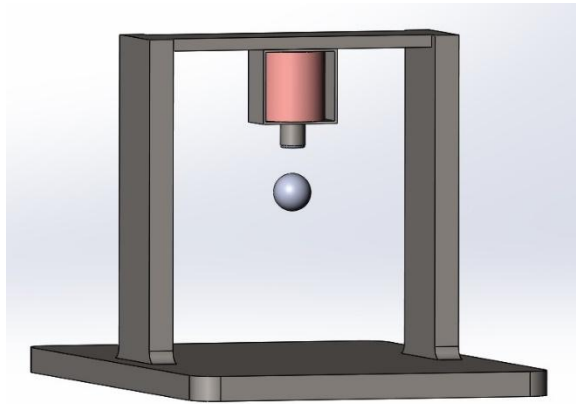


Figure 5 Prototype 3D model

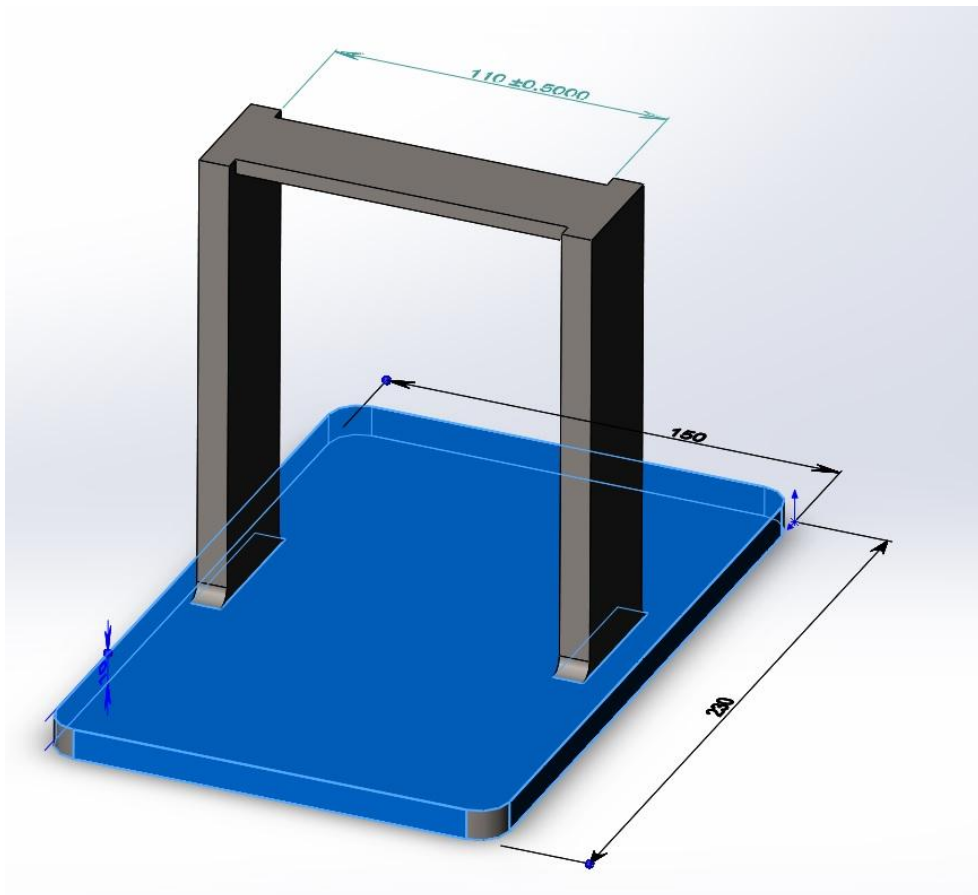


Figure 6 Dimensions

Levitation object

Any kind of ferromagnetic material can be selected as the object material for options 2, 3, 4. Proceeding from the calculations that have been done before, the weight of the object must not exceed 150 grams.

Magnetic material should be used for the implementation of variation 1. Neodymium sphere magnet has been selected (picture 7).



Figure 7 Sphere Magnet [\[5\]](#)

Permanent magnet is required, since within this control option, Hall sensors will be used, which respond to changes in the magnetic field.

Any metal object would be suitable for the implementation of all other options/variations.

Power Supply

Transformer power supply

The classical power unit is a transformer power unit. Generally, it consists of a step-down transformer or an autotransformer, whose primary coil is optimized for supply-line voltage. Then the rectifier unit is installed, which transforms alternating voltage into permanent (unidirectional pulsating). In the majority of cases, the rectifier unit consists of one diode (half-wave rectifier) or four diodes that make a diode bridge (full-wave rectifier). See diagram in figure 8.

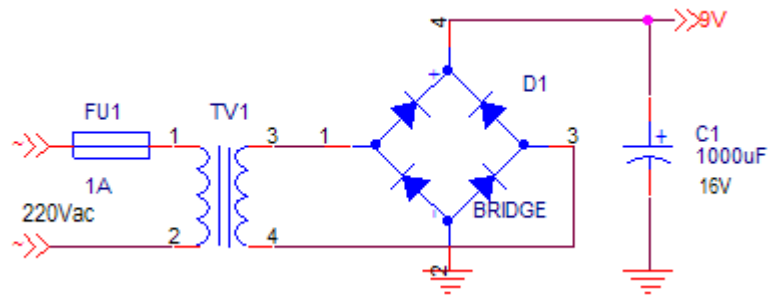


Figure 8 Scheme with diode bridge [6]

Advantages of transformer power units

- Simple structure
- Reliability
- Availability of the element base
- No radiointerference (unlike static power supply units, which generate radiointerference through harmonic constituents)

Disadvantages of transformer power units

- Heavy weight and large dimensions, especially if the power/capacity is high
- Metal intensity
- Compromise between the reduction in the efficiency coefficient and the stabilization of output potential: the stabilizer, which means additional losses, is required for providing stable voltage.

PWM Power Supply

PWM power supply units are inverter systems. In static power supply units, the alternating input voltage is first of all rectified. The obtained permanent voltage is transformed into rectangular impulses of high frequency and specific pulse ratio whether supplied to the transformer (in static power supply units with galvanic separation from supply mains) or directly to the output filter with low frequencies (in static power supply units without galvanic separation). Small-scale transformers can be used in static power supply units, which can be attributed to the fact that with an increase in frequency, the efficacy of the operation of a transformer is also boosted, while the demands for the size (cross-section) of the core, which is required for transmitting the equivalent capacity, are diminished. In the majority of cases, such core can be made from ferrimagnetic materials, unlike the core in low-frequency transformers, in which electrical steel is used.

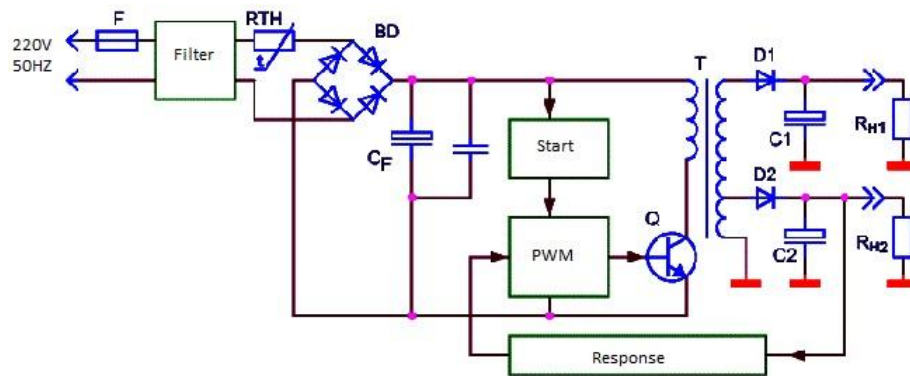


Figure 9 PWM power supply [7]

In pwm supply units (figure 9), voltage stabilization is provided through negative feedback. Feedback allows to maintain input voltage on a relatively permanent level, regardless of the fluctuations of the input voltage and load intensity. Feedback can be provided by different means. In static power supply units with galvanic separation from supply mains, the most widespread means are using feedback by means of one of the output windings of the transformer, or with the help of the optron. Depending on the feedback signal quantity (which depends on the output potential), the pulse ratio at the output of the PWM controller also changes. If separation is not needed, as a rule, a simple resistance voltage divider is used. In this manner, the power unit supports stable output potential.

Since in static power supply units the electronic devices with feedback function are used, in 99% of cases they are stabilized, i.e. provide voltage that is not dependent on load or environmental variables.

Theoretically, static power supply units do not dissipate any energy. Unlike them, linear power supply units adjust output potential and dissipate energy at the p-n junction interface of a transistor on an ongoing basis. Thus, the high efficacy of transformation is an important advantage of static power supply units as compared with linear power units. Besides, any simple static power supply unit is much smaller than a transformer unit with linear stabilizer, but as efficient.

A static power supply unit is an electronic inverter, which includes pulse controller, for the effective transformation of electric power, and the pulse-width modulator (PWM) - picture 10. Just like other power sources, static power supply units transmit power from the source of electricity mains to the load, transforming voltage on the way.

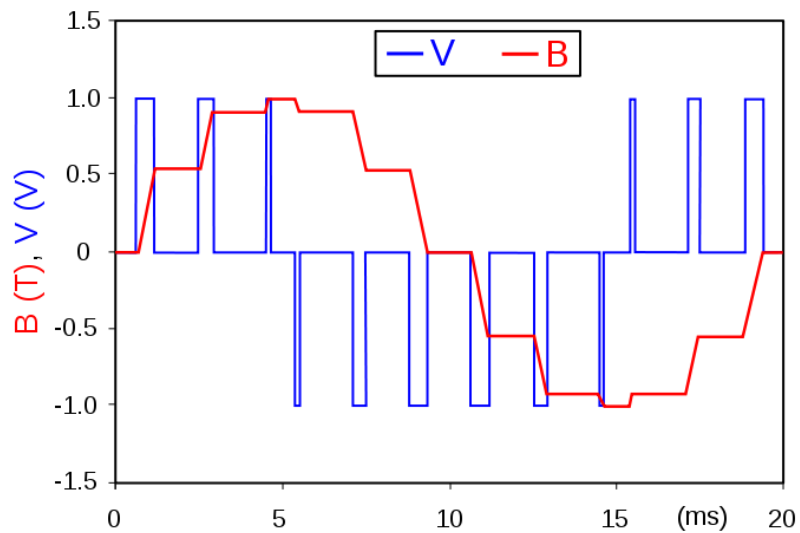


Figure 10 PWM transform [8]

Pulse-width modulation (PWM) is the operation of obtaining the variable analogue value by means of digital devices. The devices are used for obtaining rectangular pulses, i.e. the signals that switch between the maximum and the minimum values. This signal modulates the voltage between the maximum and the minimum values, alternating the duration of the make-time in relation to switching 0 V. The duration of the switching of the maximum value is called pulse width. In order to obtain different analogue values, the pulse width can be changed. For example, if power-on/off times change fast enough, the permanent signal can be applied between 0V and 3V to the light-emitting diode, adjusting its brightness. In picture 9, you can see the Duty Cycle PWM (figure 11).

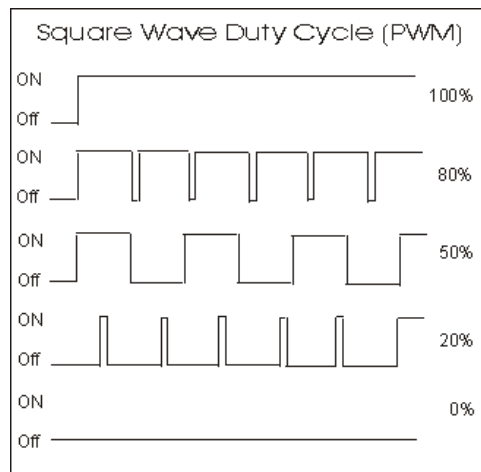


Figure 11 DutyCycle [9]

Selecting power supply.

In the result of the research, the static power supply unit has been selected for the provision of stabilized pressure. The capacity of the power supply unit will be calculated on the basis of magnet parameters. Arduino platform can be ignored, since it consumes very little energy. We will be able to calculate the maximum consumed current on the basis of coil resistance, which is 20Ω . If the voltage of 12 V, the magnet capacity makes up 7.2 W. Consequently, the minimum capacity of the power unit should be 10 W.

There are many kinds of static power supply units at the market. Mainly they can be divided into two types - frameless and with a frame. When a prototype is made that will be used in different experiments, it would be feasible to use the power unit with a frame. It will simplify the introduction of modifications into the prototype.

However, in order to make the final product, the power unit without a frame should be used. It will allow us to build a frame and accommodate all of the elements inside of it. In figure 12, you can see such power unit as well as read about its specifications.



Figure 12 PWM power supply "MeanWell" PS-25-12 [10]

Table 2 Characteristics PS-25-12

Input Voltage	90-264 VAC; 120-370 VAC
Working temperature	-10°C....+60°C
Output power	25,2 W

Controlling.

The control system has been built on the basis of the Arduino 2560 Mega hardware platform (figure 13).

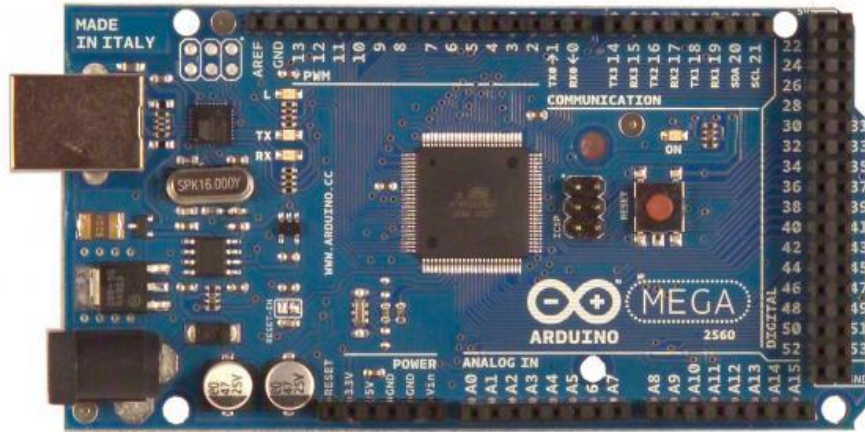


Figure 13 ArduinoMega 2560 [11]

Table 3 Arduino Specifications

Operating voltage	5B
Input Voltage (recommended)	7-12B
Output voltage (limit)	6-20B
Digital inputs/outputs	54 (14 из которых могут работать также как выходы ШИМ)
Analogue inputs	16
Permanent current through the input/output	40 mA
Permanent current for the terminal 3.3 V	50 mA
Flash drive	256 KB (из которых 8 KB используются для загрузчика)
RAM	8 KB
Non-volatile memory	4 KB
Clock frequency	16 MHz

Arduino power supply.

The network AC/DC-power adapter or the battery can be used as the external power source(not USB). Adapter plug (diameter is 2.1 mm, central connector is positive) must be plugged in the relevant power socket on the board. If power is supplied by the battery, its wires must be connected to Gnd and Vin terminals of the POWER socket.

The voltage in the external power source can be within the range of 6 to 20 V. However, when the voltage is decreased below 7V, it may lead to the reduction of voltage at the terminal down to 5V, which may result in the unstable functioning of the device. Using voltage over 12V may lead to the overheating of voltage stabilizer and the breakdown of the board. Taking all of the above-mentioned into consideration, it is recommended to use the power source with the voltage within the range of 7-12 V.

Power terminals found on the board are listed below:

- **VIN.** The voltage supplied to Arduino directly from the external power supply (not connected with 5V or USB, or some other stabilized voltage). Both the external power can be supplied through this terminal and current can be consumed if the device has been energized by the external adapter.
- **5V.** The 5V voltage from voltage stabilizer on the board is supplied to this terminal, regardless of how the device has been energized: from the adapter (7 - 12V), USB (5V), or through the VIN terminal (7 - 12V). It is not recommended to energize the device through terminals 5V and 3V3, because in this case, voltage stabilizer is not used, which may lead to the breakdown of the board.
- **3V3.** 3.3V supplied from voltage stabilizer on the board. The maximum current consumed from this terminal is 50 mA.
- **GND.** Ground terminals.
- **IOREF.** This terminal provides the information about the operating voltage of the Arduino microcontroller to expansion boards. Depending on the voltage read off from the IOREF terminal, the expansion board can switch to the relevant power source or use level converters, which allows it to operate both with 5V and with 3.3V devices.

Inputs and outputs

Using the functions of `pinMode()`, `digitalWrite()` and `digitalRead()`, each of the 54 digital outputs of Arduino Mega can be tuned to be functioning as an input or an output. The level of voltage at the outputs is limited to 5V. The maximum current that can be given out or consumed by one output is 40 mA. All outputs are linked to internal pull-up resistors (switched off by default) with the par value of 20-50 k Ω In addition to that, some Arduino outputs can perform numerous other additional functions.

CPU ATmega 2560

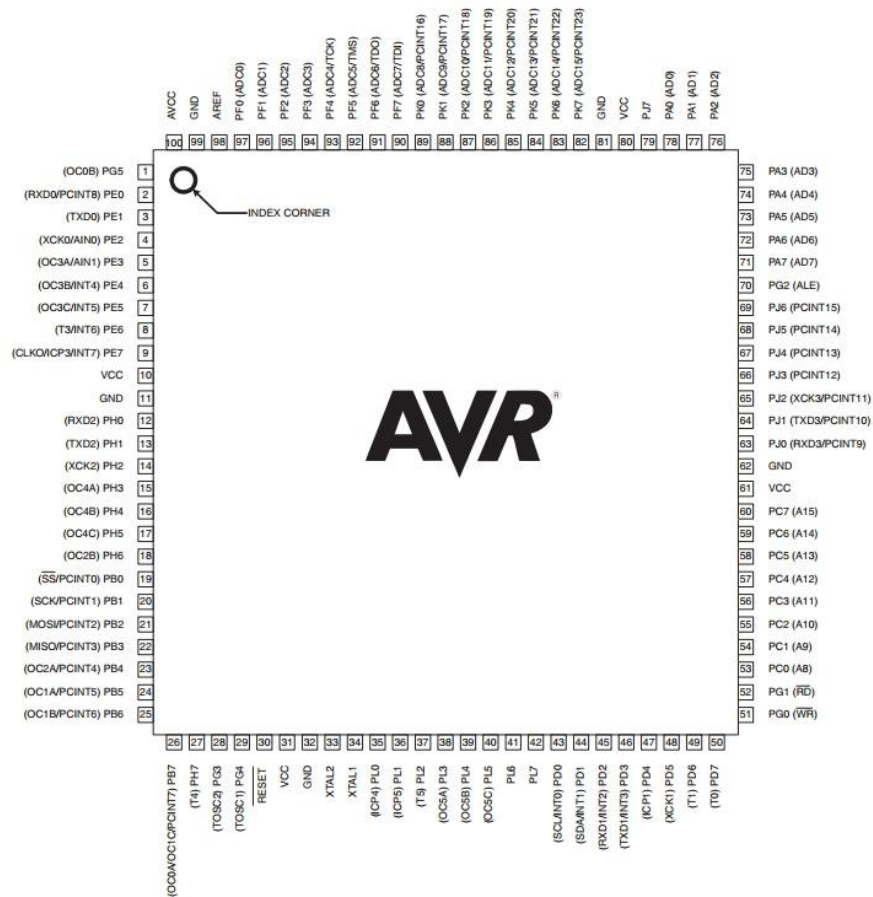


Figure 14 AVR pinout [12]

Table 4 Key parameters

Flash (kBytes):	256 kBytes
Pin Count:	100
Max. Operating Freq. (MHz):	16 MHz
CPU:	8-bit AVR
Hardware QTouch Acquisition:	No
Max I/O Pins:	86
Ext Interrupts:	32
USB Speed:	No
USB Interface:	No
SPI	5

Proceeding from the data in table 3, some simple calculations can be made in order to determine the maximum PWM output frequency. Microcontroller operates at the frequency of 16 MHz, and, consequently, the PWM counter reads off 256 values (8 bit) with the frequency of $16,000,000 / 256 = 62,500$ Hz. In the event of fast PWM, the counter is cleared when it reaches the ceiling, and 62.5 KHz is the maximum you can get. In the event of phase-correct PWM, when, after reaching the ceiling, the counter starts counting down to zero, the maximum is $62.5 / 2 = 31.25$ KHz. Some Arduino outputs are controlled by the timers on fast PWM, and others use phase-correct PWM.

If the Arduino 2560 is used, the fast PWM outputs are D4 and D13. Correspondingly, it is necessary to use these outputs to provide ultimately efficient magnet control.

Arduino is very easy to use and has a large range of options. Programming takes place by means by using the special Arduino IDE software. It operates on the basis of the most widespread operating systems, such as Windows, MACOS and Linux. The programming language for Arduino devices is Python. It is based on C/C++, easy to learn, and at present, Arduino is probably the most convenient means of programming of different devices based on microcontrollers. Using this particular platform provides a considerable decrease in the cost of the stand.

The mechanical characteristics of Arduino Mega2560 (figure 16) are listed below.

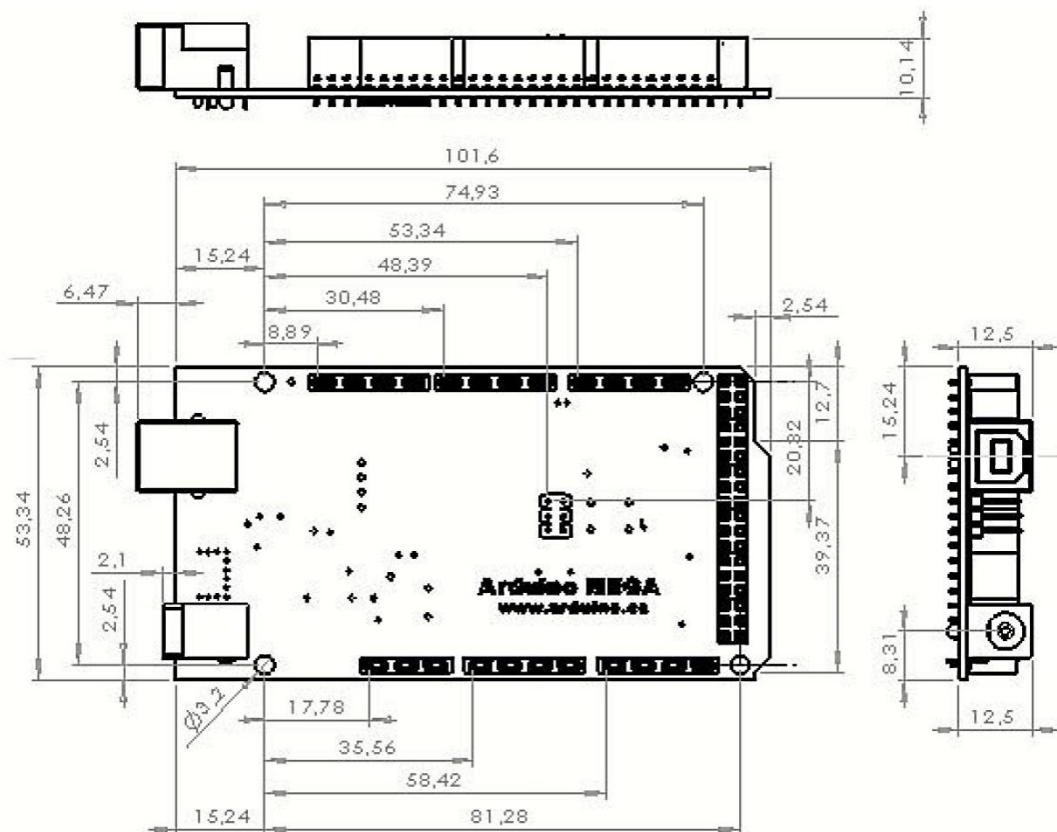


Figure 15 ArduinoMega 2560 dimensions [13]

DRIVER

High capacity consumers cannot be connected directly to Arduino. This is due to the fact that the outputs are not capable of providing the current of more than 40 mA. However, a consumer, depending on the load, may need several hundreds of milliamperes. This is how the need for an increase in capacity has emerged. As a rule, it is provided by means of transistors.

One of the ways of managing high load is using MOSFET transistors. This provides the opportunity to apply higher load, for example, to connect electric motors, electric magnets, etc., with the power supply voltage up to 40-50 volts or more and the currents of several amperes.

The connection diagram is relatively simple (figure 16).

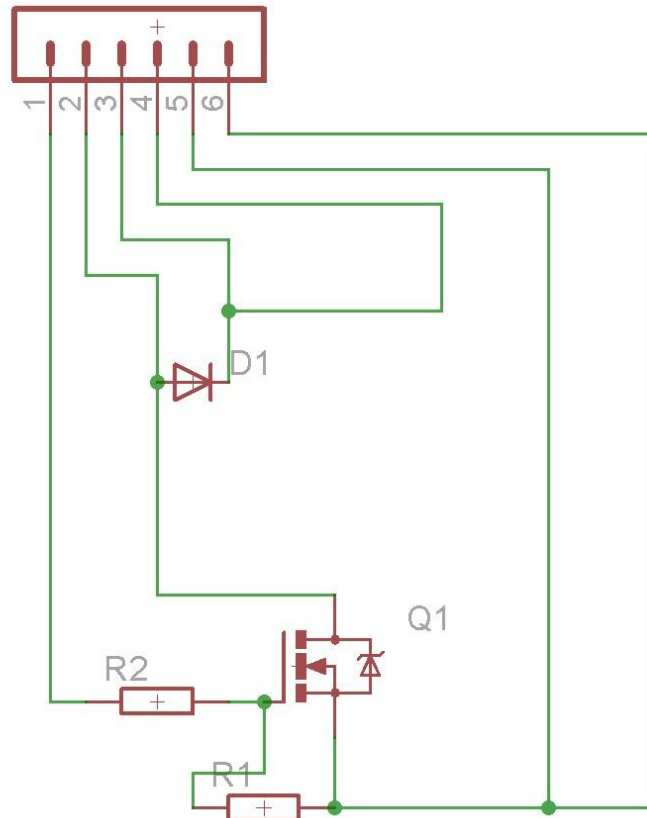


Figure 16 Wiring connection with MOSFET

- R1 – 10k Ω
- R2 – 100 Ω
- Q1 – IRL3705
- D1 – 1N4007
- Output 1 - amplifier control, PWM signal from Arduino board.
- Outputs 2;3 - application of the consumer, in this particular case, it is an electric magnet.
- Output 4 - power source 12V.
- Outputs 5;6 - common GND of the Arduino board and the power source 12V.

R1 is the pull-up resistor which is needed to guarantee maintaining the low level at the transistor gate when there is no high-level signal from Arduino. This type of connection rules out the self-starting of the transistor.

It is recommended to insert the R2 resistor with the par value of 50-150 Ω into the circuit break in the gate in order to prevent short-term current surges and provide the protection of the output of the microcontroller. When selecting MOSFET Q1, so that it would open up from the microcontroller directly, and there would be no need to place bipolar transistors or drivers in front of it, the Gate Threshold

parameter should be paid attention to, which must be about 1-4 volts. Quite often such transistors are marked as Logic Level. One of the options is the transistor IRL3705N N-Channel Hexfet Power MOSFET.

A transistor in question can endure long-lived current up to 89A (with heat removal), and it opens up when the gate voltage is 1 V ($V_{GS(th)}$ parameter). This is why we can connect this transistor to Arduino output directly.

If the load is inductive, it is recommended to use a protective diode D1, which will protect the transistor from the load of self-induction. In the result of self-induction, when managing or operating the electric motor with the help of PWM without a protective diode, such problems as the overheating of the transistor and its breakdown can arise, there will be capacity losses, etc. The smooth transistor operation is only possible through PWM. It should be pointed out that a special output on the Arduino platform should be used. In the diagram (figure 17), with the example of the function provided, too, it looks like this:

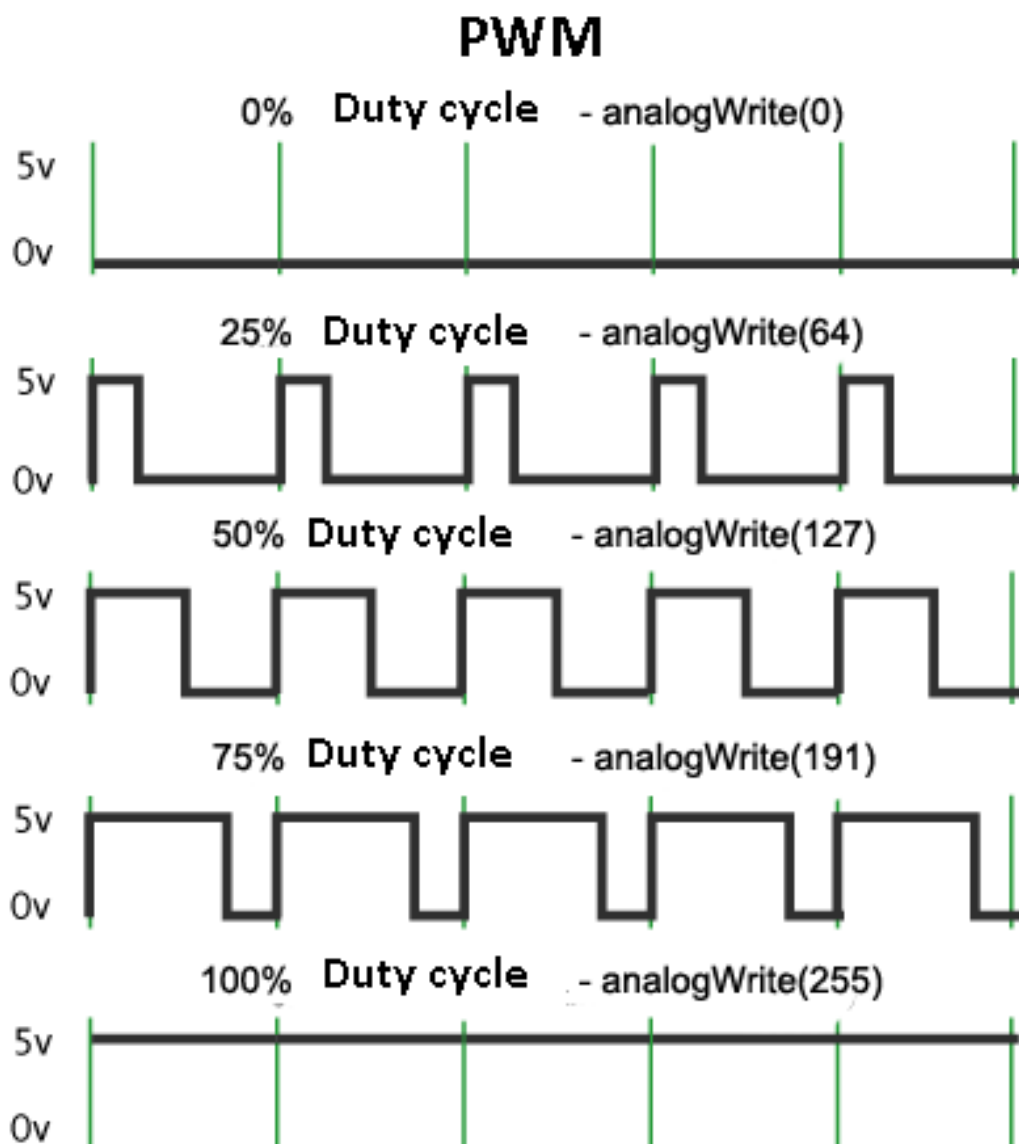


Figure 17 PWMDutyCycle [\[14\]](#)

When making the final product, all of the elements listed above should be placed on the common platform, for proper assembly. The project of the printed-circuit board is below (picture 18).

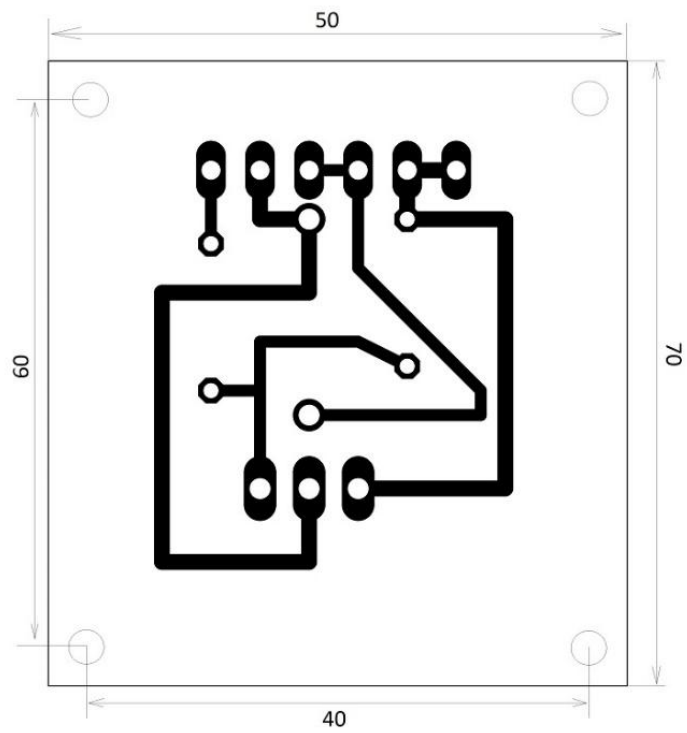


Figure 18 Board project

Feedback

Option 1 - Hall sensor

Hall sensor is a magnetoelectric device that has been named after Hall, a physician who discovered the principle, on the basis of which these sensors were developed later on. In the simplest terms, it is a sensor of the magnetic field. Nowadays Hall sensors are classified into analogue and digital sensors.

- **Digital sensors** determine the existence or the absence of the field. It means that if the induction has reached a certain threshold, the sensor signals the existence of the field in the form of some logical unit, while if the threshold has not been reached, the sensor displays the logical zero. In other words, if the induction is weak, and, correspondingly, the sensor sensitivity is also weak, the existence of the field may not be detected/registered. The disadvantage of a sensor like that is the existence of dead zones between thresholds.

Digital Hall sensors are also divided into: bipolar and unipolar.

1. **Unipolar** sensors go off if there is a field of specific polarity, and they switch off when the induction of the field decreases.
 2. **Bipolar** sensors respond to changes in field polarity, i.e. one polarity switches the sensor on, while another one switches it off.
- **Analogue Hall sensors** transform field induction into voltage. The value displayed on the sensor depends on the type of polarity and its strength. However, the distance, at which the sensors are set up, should also be taken into consideration.

In this particular case, the analogue sensor will be used, since we are interested in the precise positioning of the sensor. Figure 19 contains the depiction of transfer characteristic on the example of the sensor SS495B.

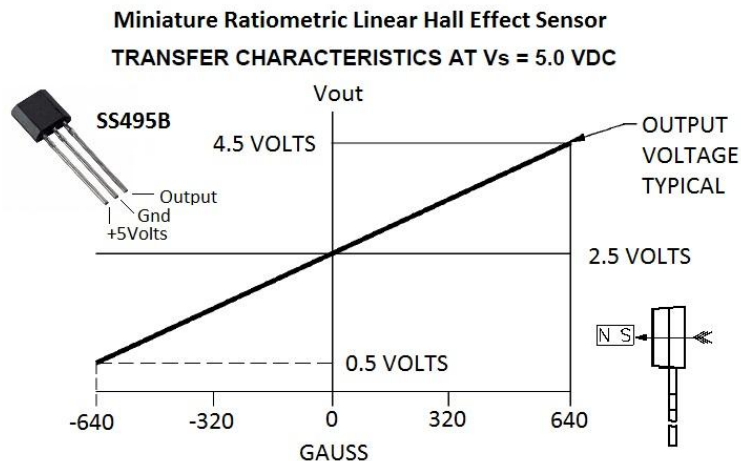


Figure 19 Transfer characteristic [16]

For the variations of the system control with the help of inductive sensors or Hall sensors, the SS49 sensor has been used (figure 20). This method is quite simple, since basically it does not require digital control. The entire system can be analogue. In spite of that, we will be using Arduino, because it will not be possible to build further variations in analogue format.



Figure 20 Hall sensor [16]

The principle of operation of this variation consists in the measurement of the force of magnetic field with the help of Hall sensors. The advantage of this method is that the system is virtually isolated from different external influences. Thus, it will be more stabilized than the others. The disadvantage is the use of a permanent magnet as the targeted object. Another important aspect is that the electric magnet, going on and off, will create the magnetic field, which will intercept Hall sensor. Thus, the values will be changing all the time, and it will be impossible to determine the precise position of the object. In order to avoid that, two Hall sensors should be used. The first one should be installed beneath the magnet, and the second one should go above the magnet (picture 21). Both sensors must be installed in one direction. If magnet winding has been wound symmetrically, the field will be even on both sides, but there will be no object above the magnet, which will enable us to see the difference in sensor values and use it as a steering signal.

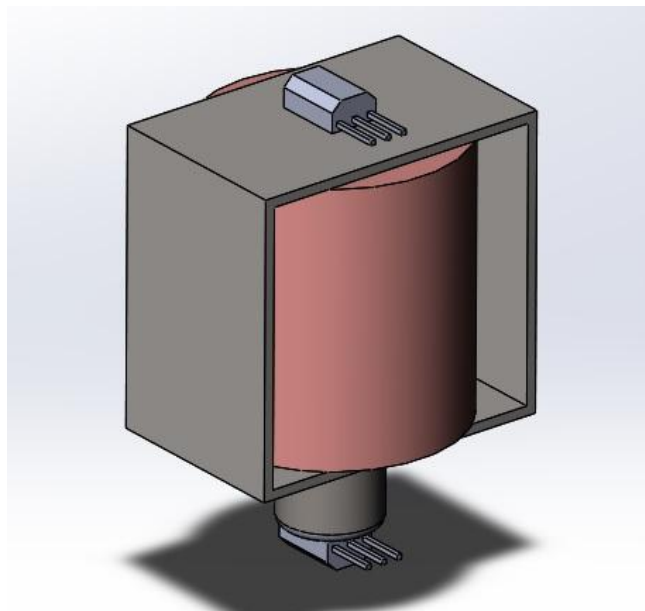


Figure 21 Sensors installation

The variations of connection of the sensor to the Arduino platform are described below (picture 22), and the straightforward code for data acquisition is provided.

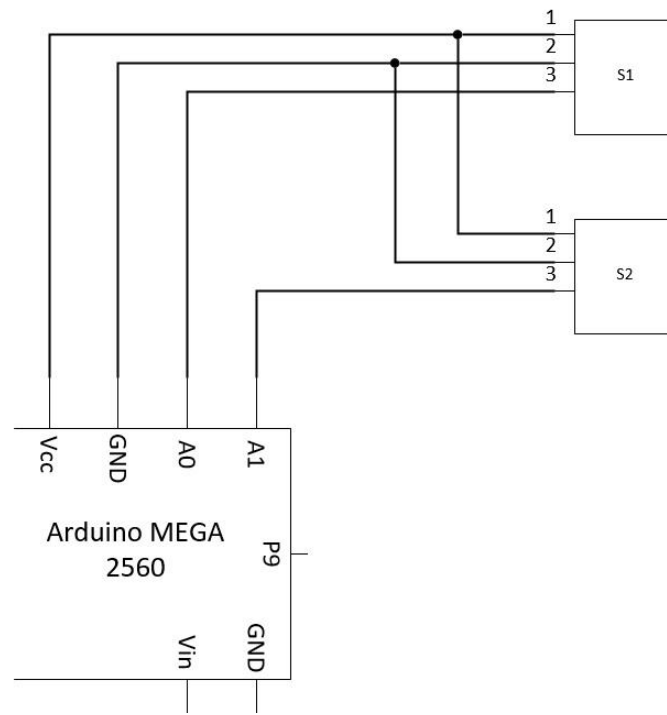


Figure 22 Hall sensors connection

```





1.  const int in1 = A0; // Analog input Hall sensor
2.  int s = 0; // Hall sensor value
3.
4.  void setup()
5.  {
6.  //
7.  Serial.begin(9600);
8.  }
9.
10. void loop()
11. {
12. s = analogRead(in1); // read value Hall sensor
13. Serial.print("Hall sensor = ");
14. Serial.print(s1); // Print value
15. }

```

Option 2 - Distance sensor

This method is based on the measurement of the distance to the object and, proceeding from the obtained data, the measurement of voltage on electric magnet will be done. Since the distance sensor will be used as a control unit, the most accurate sensor must be selected. This will allow us to control the electric magnet in the most efficient way. Table 5 below compares different types of distance sensors.

Table 5 The comparative analysis of different distance sensors

	Inductive	Ultrasonic	Triangulate	Radar
				
Distance	0...20 mm	10 mm ...10m	10...1,000 mm	10 mm ...1 km
Resolution	0.1 MKM	0.1 mm	1 MKM	0.5 mm
Accuracy	1 MKM	0.2 mm	2MKM	2 mm
Linearity %	0.4-5	0.5	0.05-1	0.001
Time, ms	0.3	20	1	1

Proceeding from the table above, it can be said that ultrasound sensors meet the requirements and are the cheapest option. This will allow to reduce the price of the stand considerably. For cost reasons, the ultrasound sensor HC-SR04 (figure 23) has been selected for our stand.



Figure 23 HC-SR04 [17]

Technical specifications of HC-SR04

- Voltage supply: +5V – permanent current;
- Current strength when idle: < 2 mA;
- Current strength when in operation: 15 mA;
- Effective operating angle: < 15°;
- Measuring distance: from 2 cm to 400 cm (1-13 inches);
- Resolution capability: 0.3 cm;
- Measuring angle: 30 degrees;
- Trigger pulse width: 10 microseconds;
- Dimensions: 45 mm x 20 mm x 15 mm.

The ultrasound distance sensor is the HC-SR04 module which uses acoustic radiation for determining the distance to the object. This wireless sensor provides high precision and stability of measurements. Measuring range: from 2 cm to 400 cm. Sun radiation and electromagnetic noise virtually do not affect sensor values. The module is sold in one set with the transmitter and the receiver.

The principle of sensor operation (figure 24) can be provisionally divided into 4 stages:

1. The pulse that is 10 μ s long is fed to the Trig output.
2. Inside the distance meter, the input pulse is transformed into 8 pulses with the frequency of 40 KHz and sent forward.
3. When the pulses reach an obstacle, they are reflected and received. What we get is the signal output at the Echo output.
4. Immediately on the side of the controller we transform the received signal into distance using the formula:
 - pulse width (μ s) / 58 = distance (cm)
 - pulse width (μ s) / 148 = distance (inch)

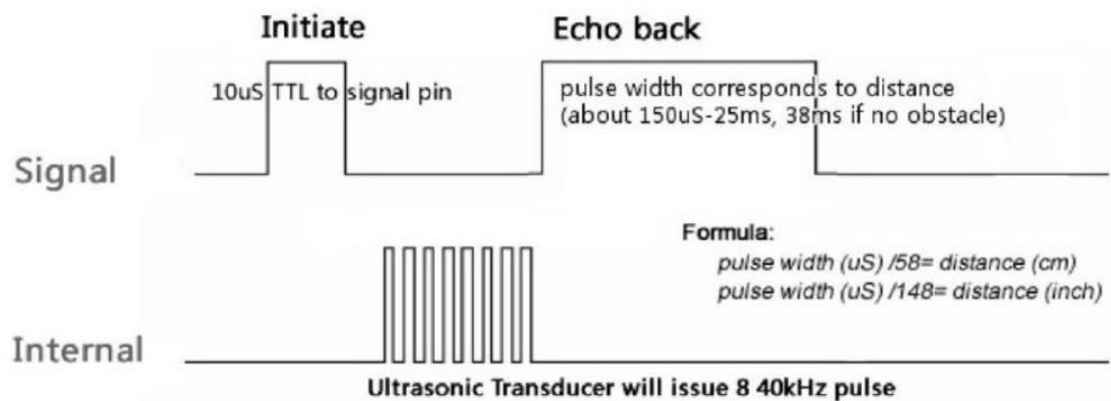


Figure 24 Waveform of the sensor HC-SR04 [17]

Proceeding from the specifications, we can assume that the sensor should be installed at the distance of at least 20 mm from the object. Another critical parameter is the resolution of the sensor. It is 3 mm, which, in fact, is quite poor accuracy and can have a negative effect on system operation. In spite of that, we must test in real life whether this sensor is suitable or not. Below, there is an example of the connection of sensor to the Arduino hardware platform as well as the function code in the ArduinoIDE environment for changing the distance either in centimeters or in inches.

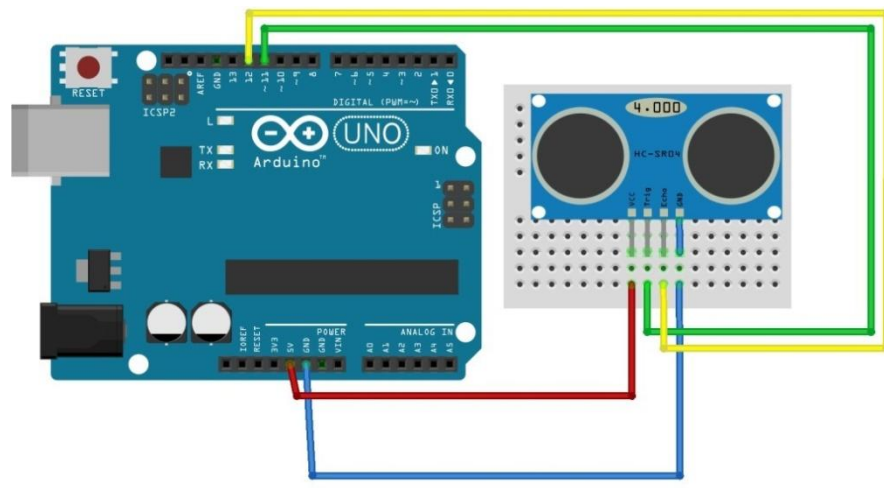


Figure 25 Wiring connection HC-SR04 [18]

```

1.  int trigPin=11;//Trigger – green conductor
2.  int echoPin=12;//Echo – yellow conductor
3.  long duration, cm, inches;
4.  void setup(){
5.    //Serial Port begin
6.    Serial.begin(9600);
7.    //Initializing inputs and outputs
8.    pinMode(trigPin, OUTPUT);
9.    pinMode(echoPin, INPUT);
10. }
11. void loop()
12. {
13.  digitalWrite(trigPin, LOW);
14.  delayMicroseconds(2);
15.  digitalWrite(trigPin, HIGH);
16.  delayMicroseconds(10);
17.  digitalWrite(trigPin, LOW);
18.  // We read the data from the ultrasound sensor: HIGH value, which depends on the interval (duration; in
    microseconds) between sending out the acoustic wave and receiving it back at the ultrasound scanner.
19.  pinMode(echoPin, INPUT);
20.  duration =pulseIn(echoPin, HIGH);
21.  // transformation of time into distance
22.  cm =(duration)/58;
23.  inches =(duration)/148;
24.  Serial.print(inches);
25.  Serial.print("in, ");
26.  Serial.print(cm);
27.  Serial.print("cm");
28.  Serial.println();
29.  delay(250);
30. }

```

Option 3 - Photo resistor

This is the easiest way to monitor the position of a levitating object. It consists in using the optical pair, i.e. the infrared emitting diode and a phototransistor set up in one line. When the object is below the line, the system switches on the magnet, which draws the object, and when the object breaks the line, the magnet switches off. The main advantage of this option is that it is easy to implement. However, it also has a considerable disadvantage, namely the system does not know the exact location of the object, which makes the monitoring of the location of the object much more complicated. In order to solve this problem, several phototransistors must be put up at different heights (figure 26). This will allow to determine the position of the object in relation to the the magnet.

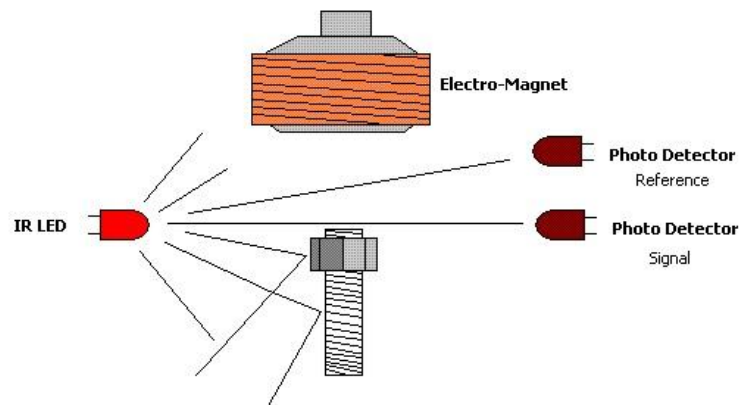


Figure 26 Location of photo resistors [19]

Below (figure 27) there is an example of connection of the infrared diode and infrared receiver to the Arduino platform as well as the example of the code for determining the output status of the infrared receiver.

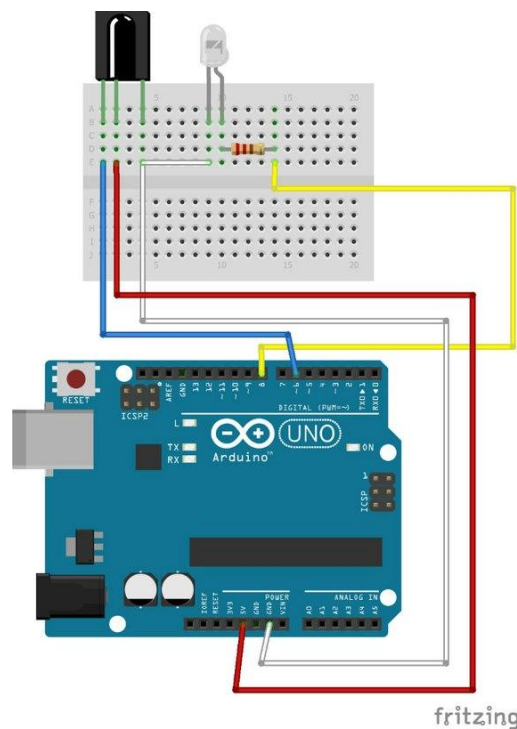


Figure 27 Ir system connection [20]

```

#include "IRremote.h"

IRrecvirrecv(6); // Indicating the PIN, to which the receiver has been connected

decode_results results;

void setup()
{
  Serial.begin(9600); // Set the speed of the serial port

  irrecv.enableIRIn(); // Launch data receipt
}

void loop(){
  if(irrecv.decode(&results)) // If the data has arrived
  {
    Serial.println(results.value, HEX); // Send the received data into the console

    irrecv.resume(); // Receive the next order
  }
}

```

In this code [21], we have used the “IRremote.h” library. It contains everything that is needed for using the infrared Tsop receiver. With the help of this code, any kind of infrared radiation can be received in HEX-format.

Option 4 - Camera.

This particular option assumes the use of any kind of digital camera as a sensor. In order to turn the camera into the system detection device, the Machine Vision should be used.

The algorithm of the operation of the Machine Vision is the receipt and further processing of data, using passive devices for image capture, and a digital camera is one of them. Unlike using other sensors, this method brings the operation of the system of Machine Vision (especially stereoscopic vision) extremely close to the one used by people for accomplishing visual tasks. In other words, at the input, both the robotic system and a human being are provided with similar visual information. Only the algorithm and the computation capacity that are used for transforming and interpreting the information are different. As an example, an ordinary web camera has been selected. The specifications of this camera meet the requirements that exist within the control system.

After the image has been captured, it must be processed in the Labview environment. This kind of image processing is called Image Recognition. With the help of the Labview, we can retrieve all of the necessary parameters from the image with their further conversion into Ccode.

Of course, the connection of the camera and further conversion of the image assume the availability of sufficient amount of resources. This aspect makes the prospects of the implementation of this cheap solution much more complicated and challenging. In the process of building a prototype using this technology, all possible measures aimed at resolving this problem will be taken.

As an example, let us have a look at the OV5642 module (figure 28). Similar modules perfectly fit into the projects related to photography and videostream. Besides, they usually have a built-in capacity for adjusting the brightness and saturation of colours, auto contrast and auto brightness settings, and allow to monitor movement.

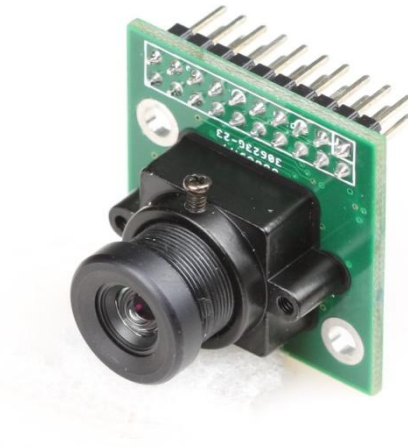


Figure 28 Camera module OV5642 [22]

The camera module has high resolution, i.e. 2592 x 1944 pixels. The camera is sensitive to infrared radiation, due to which it can detect changes in colour reproduction. The camera module is meant for monitoring, and also for taking pictures of relatively high quality. There are modules with other parameters. The one we are reviewing is one of the best of them in terms of its technical specifications.

Table 6 OV5642 Specificatinos

active array size:	2592 x 1944
power supply:	core: 1.5VDC + 5% (internal regulator) analog: 2.6 ~ 3.0V I/O: 1.7 ~ 3.0V
output formats:	(8-bit): YUV (422/420) / YCbCr422, RGB565/555/444, CCIR656, 8-bit compression data, 8/10-bit raw RGB data
lens size:	1/4"
input clock frequency:	6 ~ 27 MHz
shutter:	rolling shutter
maximum image transfer rate:	5 megapixel (2592×1944): 15 fps (and any size scaling down from 5 megapixel) 1080p (1920×1080): 30 fps 720p (1280×720): 60 fps
scan mode:	progressive
pixel size:	1.4 μm x 1.4 μm
image area:	3673.6 μm x 2738.4 μm

Our task is to monitor the object. The more frequently the system will be provided with the information about the position of the object, the more accurate the monitoring/control will be. This module provides an opportunity to make videos with the speed of 120 shots per second, which enables us to forward the data to the controller 120 times per second. This is quite a good specification of a modern camera which is relatively cheap.

The programming of the camera should start with proper connection. The voltage at camera inputs in some places is different from the voltage on Arduino, which is why we need resistors.

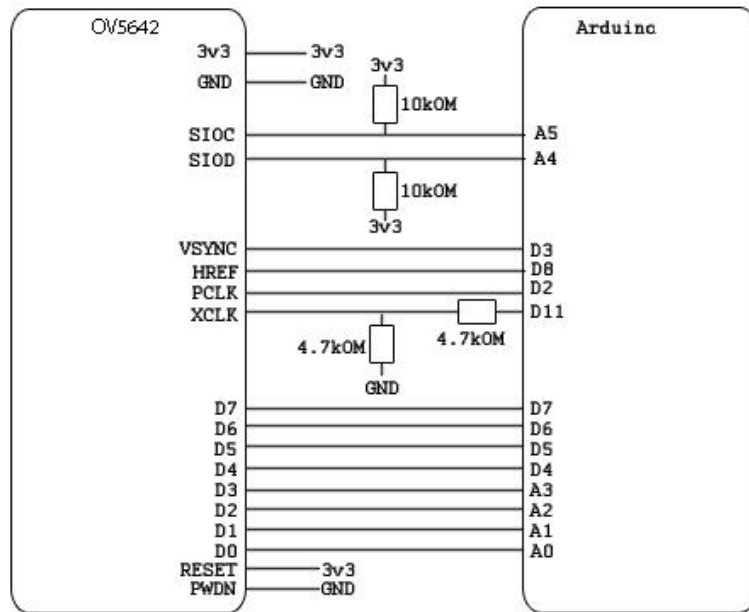


Figure 29 Camera connection [22]

Oscillogram should be provided (figure 30), which will make it perfectly clear as to what kind of signals with high and low values we are expecting.

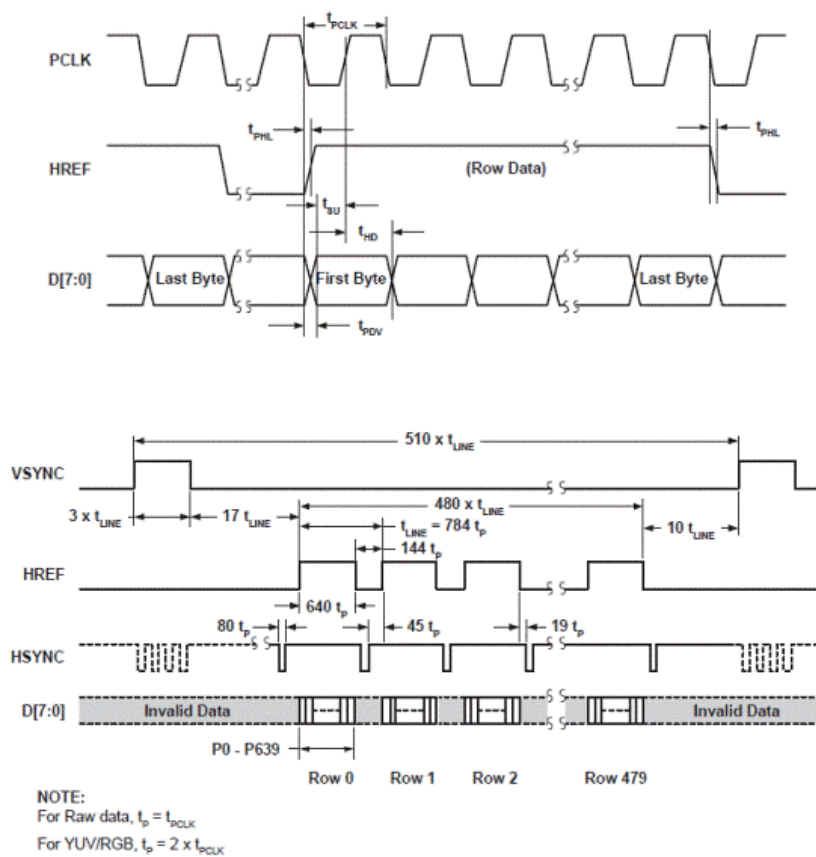


Figure 30 Oscillogram VGA [22]

Example of the code [22] for retrieving the image via the Arduino environment.

```
StringPgm(PSTR("RDY"));

//VSYNC
while(!(PIND &8)); //wait for high
while((PIND &8)); //wait for low

y = hg;
while(y--){
  x = wg;
  while(x--){
    //PCLK
    while((PIND &4)); //wait for low
    UDRO = (PINC &15) | (PIND &240);
    while(!(UCSR0A &(1<< UDRE0))); //wait for byte to transmit
    while(!(PIND &4)); //wait for high
    while((PIND &4)); //wait for low
    while(!(PIND &4)); //wait for high
  }
}
_delay_ms(100);
```

Implementation and analysis of control options.

The implementation of option 1

Algorithm 1 - Proportional.

Key element:

- 2x Hall sensors SS495B

As it has already been discussed before, sensors must be attached on both sides of the magnet. Since the field will stretch in different directions, the sensors must also be attached opposite each other. It should also be pointed out that the field may be asymmetrical, and the sensors might be located not precisely opposite each other or the magnet. In order to take due account of all of the deviations and errors, the allowance must be calculated. In order to calculate the allowance, the programme for adjusting sensor readings must be developed. At this stage, the main task is to measure the difference in readings in order to calculate the allowance.

The most difficult thing about this task consists in the fact that to provide stabilization when the status of the output of the controller is changed, about five milliseconds have to pass before it can be done, because of the high level of magnet inductance.

In order to reduce this interval, the magnet can be controlled smoothly, without switching it on and off, but adjusting its capacity a little. On Arduino, this can be done with the help of the PWM-output. PWM (Pulse Width Modulation) is the means for changing the output voltage smoothly and evenly, using only digital statuses (figure 31).

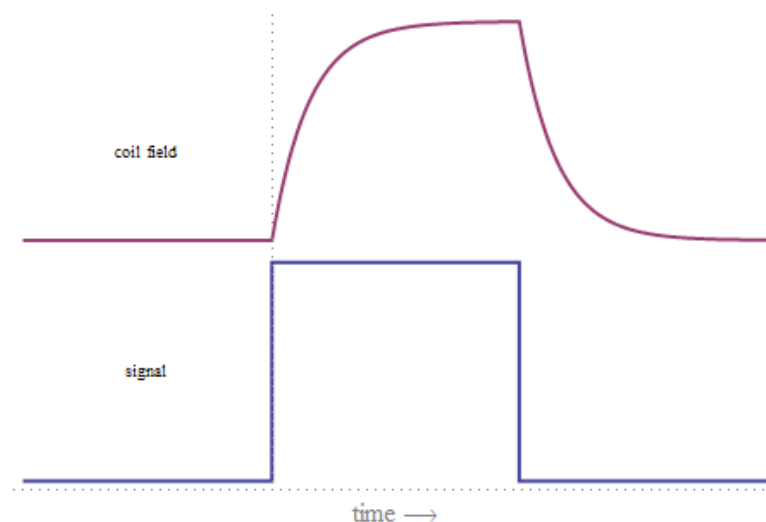


Figure 31 PWM and magnet induction [23]

It means that some of the time the output is on, while in the remaining time period it is off, but because of inertia, the scheme describing the output is always being on but with half-power is in operation. In picture 16, you can see the ratio between the PWM and magnet inductance.

The aim of the calibration programme is to find the value displayed by Hall sensors when the magnet is on and off, with due consideration of inertia. In the result, we will get two values which will be used in the future for the purposes of the control programme. These are the differences between the values displayed by Hall sensors with 10% and 100% of voltage applied on the magnet. The programme [24] is described below, and comments are provided.

```
int in1 = A0; // analogue input of Hall sensor 1
int in2 = A1; // analogue input of Hall sensor 2
int out1 =10; // output (PWM) to magnet
int s1 =0; // Hall sensor value 1
int s2 =0; // Hall sensor value 2
int o1; // Output
void setup()
{
  Serial.begin(9600);
}
void loop()
{
  analogWrite(out1,255); // magnet status 100%
  delay(15); // waiting while the magnet switches off
  s1 =analogRead(in1); //reading the first Hall sensor
  s2 =analogRead(in2); // reading the second Hall sensor
  o1 = s2 -s1; // calculating the differences at inputs
  Serial.print("magnet on: s1 = ");
  Serial.print( s1 );
  Serial.print(" s2 = ");
  Serial.print( s2 );
  Serial.print(" diff-on = ");
  Serial.print( o1 );
  analogWrite(out1,25); // magnet status 10% of capacity
  delay(15); // waiting while the magnet switches off
  s1 =analogRead(in1); //reading the first Hall sensor
  s2 =analogRead(in2); // reading the second Hall sensor
  o1 = s2 -s1; // calculating the differences at inputs
  Serial.print("magnet off: s1 = ");
  Serial.print( s1 );
  Serial.print(" s2 = ");
  Serial.print( s2 );
  Serial.print(" diff-off = ");
  Serial.println(o1); // moving to the new line in the end
  delay(1000); //
}
```

In the result, two values have been obtained: difference on and difference off. In the final programme, they will be used as a starting point within the control system. The final stage of the programme is described below.

```
const int in1 = A0; //analogue input of Hall sensor 1
const int in2 = A1; //analogue input of Hall sensor 2
const int in3 = A2; //analogue input of the variable resistor
const int d10=<diff-off>; //10% of capacity
const int d100 =<diff-on>; //100% of capacity
const int out1 =4; //output (PWM) to magnet.

int s1 =0; // Hall sensor value
int s2 =0; // Hall sensor value
int o1 =255; //output status by default
int d =0; // allowance
int v; // final value from sensors

void setup(){
  TCCR0B = TCCR0B & B11111000 | B00000001; // increasing the frequency of PWM for outputs D4 and D13
  (62500Hz)
}

void loop()
{
  s1 =analogRead(in1); // reading the values on Hall sensor
  s2 =analogRead(in2); // reading the values on Hall sensor 2
  v =abs(s1- s2) +d ; // difference with absolute allowance
  d =map(o1,25,255, d10, d100); // calculating the allowance
  o1 =map(v,0,1024,25,255); // calculating the output
  analogWrite(out1, o1); // entering the relevant status of the magnet in the output
  delayMicroseconds(100); // waiting for some time until the analog-to-digital converter is ready to read the data
}
```

In the code [24], a special setting of the PWM frequency is used. The standard meaning for outputs 4 and 13 is about 1 kHz. In the course of the experiment, with frequency specified above, the system had major fluctuations. In the result, the object lost stability and fell down. In order to resolve the problem, we had to increase the frequency of PWM. The manufacturers of Arduino have provided the relevant setting. After we had made sure that the selected transistor can operate on high frequencies, the maximum acceptable frequency was selected, i.e. 62,500Hz.

After that, with the help of the map function, we carried over the values from the output o1 into the value range diffoff and diffon. Thus, we got the allowance d.

For analysing the results, the monitoring function was added into the code. The diagram we have drawn is below (picture 32).

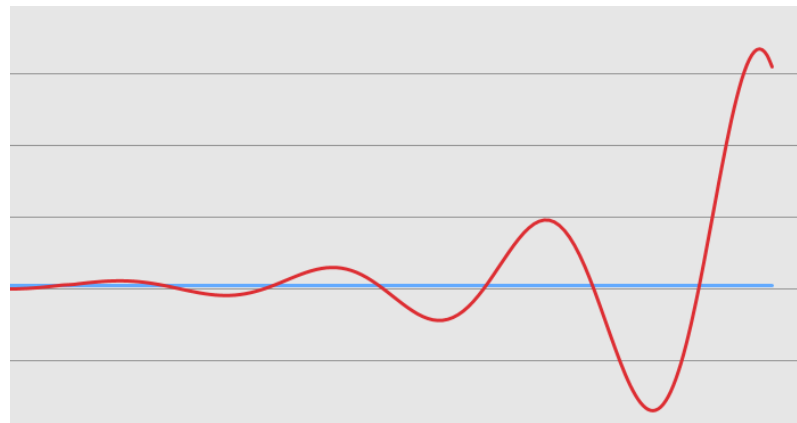


Figure 32 Result of controlling by algorithm 1

As you can see, after the relatively fast stabilization of the object, fluctuations appear in the system. As the fluctuations are increasing, the system is destabilizing.

Algorithm 2 - PID

It is used in the systems of automatic control for the purposes of forming the steering signal with the aim of obtaining the required accuracy and quality of the transition process. The PID controller forms the steering signal, which is the total of the three components, the first of which is proportional to the difference between the input signal and the feedback signal (loop error signal), while the second one is the integral of the loop error signal, and the third one is a derivative of the loop error signal.

$$u(t) = P + I + D = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{de(t)}{dt}$$

Let us review each of the components individually. P, or Proportional band - we take the difference between the current value and the desired value, multiply by the configurable factor, and get the capacity that must be generated at a specific moment. This is the proportional component which is efficient at the moment when error signal occurs, i.e. it responds immediately both to the changes in the desired value and in the behaviour of the object. If the pre-set value is achieved, the system output switches off until the current value does not become smaller than the pre-set one. When it happens, the system resumes the process. This kind of adjustment has its own disadvantages, i.e. the effect manifests itself with a delay, while the object is not only affected by us, but also by the environment: for example,

the heated reactor is not only hot inside, but it also emits heat into the room, and when we turn it off, it cools down. This is why the pure proportional regulator fluctuates around supporting points, and the stronger it fluctuates, the more considerable the environmental effect becomes. In picture 33, you can see the diagram of adjustment of the P regulator.

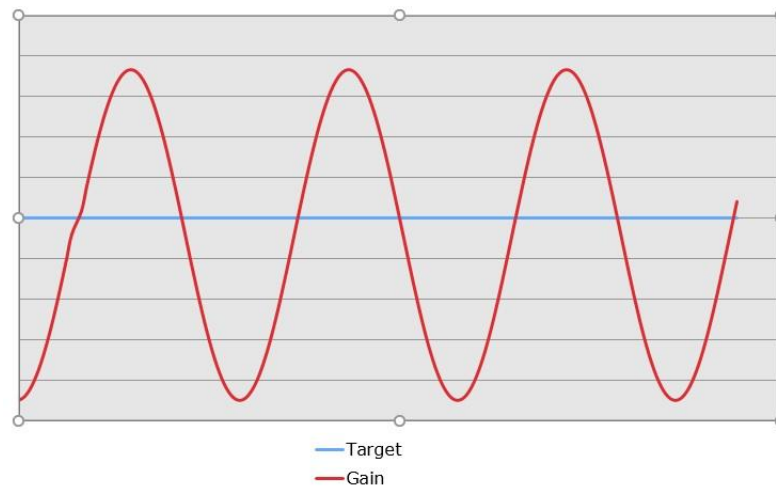


Figure 33 P regulator

In order to compensate for the "external" effects exerted on the object, the integral component is included into the circuit. All errors that were detected in the system are forwarded to the integrator. The accumulated integral, with its own coefficient, causes its own surplus to/diminishing of capacity. In the result of such approach, if the process is stationary, after some time, the integral will select the capacity contribution that will compensate for the losses caused by the environment, and fluctuations disappear, the integral becomes stable, which is why the value of the output capacity becomes permanent. What is more, since the desired temperature is maintained, and there are no errors, the proportional component is totally inactive. In picture 34, you can see the diagram of adjustment of the PI regulator.

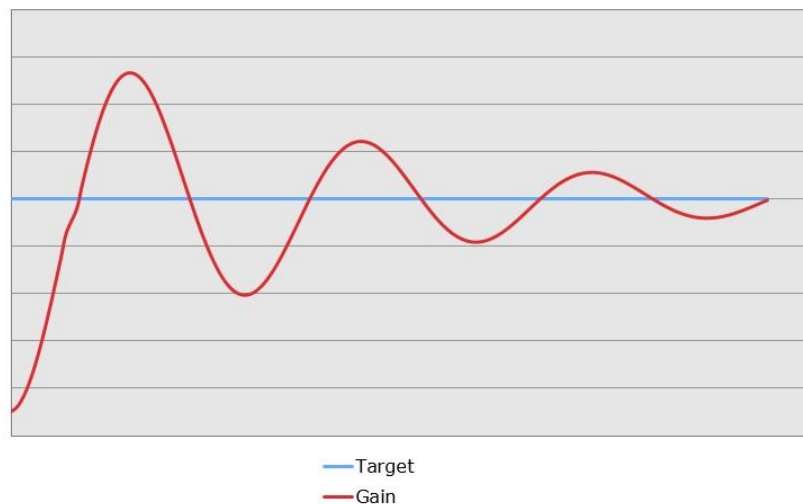


Figure 34 PI regulator

In order to compensate for the effect the delays between the impact on and the response of the system might have, the differential component is added into the system. The proportional regulator exclusively provides capacity all the time, until the pre-set value has been achieved, while the proportional-differential regulator starts reducing the power before reaching the desired value, since the number of errors is reduced, and there is a negative derivative that reduces the impact. It allows to minimize overcorrection in the event of major transitions (figure 35).

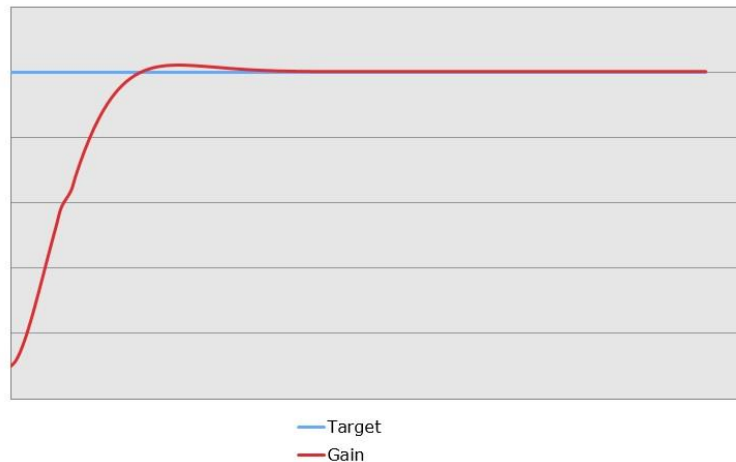


Figure 35 PID regulator

In order to manage the system with the help of PID, the code for the implementation of this type of control is required. In the ArduinoIDE environment there is a library "Pid_v1.h". In this library, you can change KpKi and Kd parameters. This will allow you to adapt the regulator to the system in question and boost its efficacy considerably. The difference between the values displayed by Hall sensors (see first variation) will be used as the desired value.

The example of the control code [25] is provided below.

```
#include <PID_v1.h>
int in1 = A1;
int in2 = A2;
int out =5;
int s1;
int s2;
int s;
int v;

//Define Variables we'll be connecting to
double Setpoint, Input, Output;

//Specify the links and initial tuning parameters
PID myPID(&Input, &Output, &Setpoint,2.3, 22.2, 0.1, DIRECT);
```

```

void setup()
{
  Setpoint = 310;

  //turn the PID on
  myPID.SetMode(AUTOMATIC);
}

void loop()
{
  s1 = analogRead(in1);
  s2 = analogRead(in2);
  v = s2-s1;
  s = s1-v;
  Input = s;
  myPID.Compute();
  analogWrite(4,Output);
}

```

Prototype cost

Table 7 Prototype 1 cost

ArduinoMega 2560	35€
SS495B 2x	10€
Magnet	20€
Wire connections	5€
Frame	20€
Driver	10€
Итого	100€

The amount above does not include the cost of designing.

Conclusion

When using the algorithm 1, the system is stabilized quite fast, and no complex computation processes are involved. However, the system is not always stable. The error has been calculated/estimated roughly, which is why system upsets and disruptions can occur. In order to fix it, the control system is required, which would respond to errors immediately and rectify them.

The algorithm of exercising control with the help of the PID controller has also been examined. This method has provided a solution to the problem. This can be attributed to the availability of the differential component.

The implementation of option 2

Algorithm 1 – ONOFFcontroller.

Key element:

- Ultrasound sensor HCSR04

Almost all ultrasound sensors have the so-called "blind area". It means that the sensor should be installed beneath the object at the distance of at least 20 mm. In our case, the distance between the sensor and the magnet is about 160 mm. Such distance is within the effective range of the sensor. In picture 20, you can see the prototype with the installed sensor.

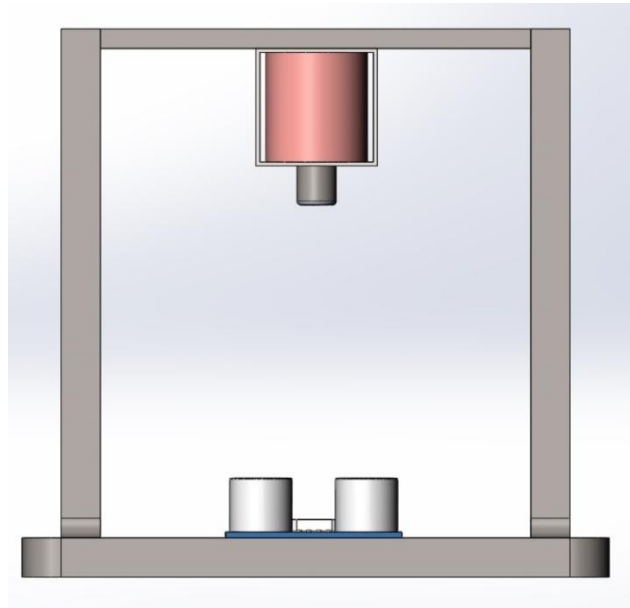


Figure 36 HCSR 04 installation

The pre-set height value depends on the weight of the object and will be determined in the course of experiment. The disadvantage of this option is that the ultrasound sensor is not effective with respect to the rounded shape of the object. The object with the straight surface should be used so that the measurements would be the most accurate.

A very simple code is used:

```
into1;  
int v;  
intechoPin=9;  
intrigPin=8;  
intledPin=13;  
int FAN =5;  
void setup(){
```

```

TCCR3B = TCCR3B & B11111000 | B00000001;

Serial.begin(9600);

pinMode(trigPin, OUTPUT);

pinMode(echoPin, INPUT);

pinMode(ledPin, OUTPUT);

pinMode(FAN, OUTPUT);

}

unsigned int impulseTime=0;

unsigned int sm=0;

void loop(){

int duration, cm;

digitalWrite(trigPin, HIGH); /* The pulse is fed to the trig input of the distance meter */

delayMicroseconds(10); // equals to 10 microseconds

digitalWrite(trigPin, LOW); // Switched off

impulseTime=pulseIn(echoPin, HIGH); // Measure the length of the pulse

sm=impulseTime/5.8; // Convert to centimeters

Serial.println(v); // Bring to the port

delay(100);

if(v < 165)

{

analogWrite(out, 255);

}

else

{

analogWrite(out, 100);

}

}

```

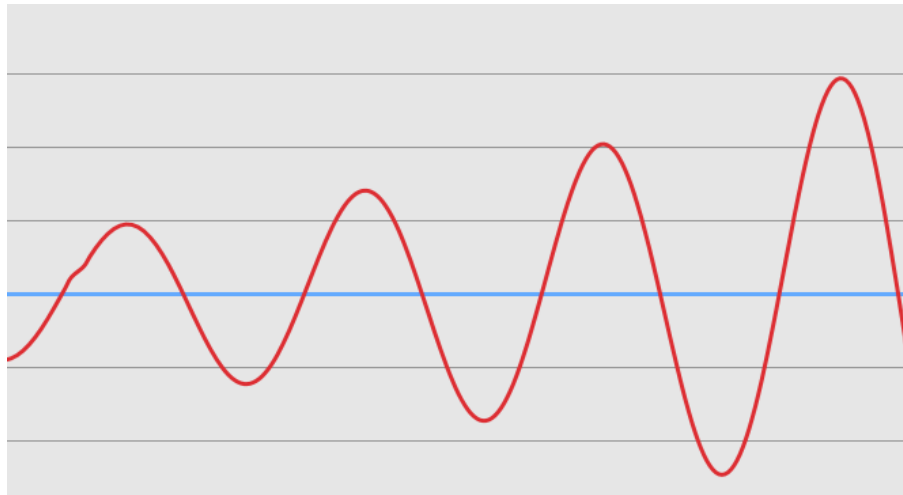





Figure 37 Controlling plot HRSR04

In the result, the system that we get is very unstable (figure 37). After having a closer look at the control diagram, you will see that the system identifies the position of the object incorrectly. The reason could be the inaccuracy of measurements related to very poor accuracy of the HCSR 04 sensor. In order to resolve the problem, the ultrasound distance sensor of some other type should be used. As an example, let us have a look at the UM18-217161101 sensor, produced by SICK. The sensors are compared in table 3.

Table 8 Comparison ultrasonic sensors

	UM18-217161101 	HC-SR04 
Диапазон	20-150 mm	20-4000mm
Ultrasonic frequency	380 kHz	40 kHz
Power supply	10-30 V	5 V
Resolution	0,2 mm	3mm
Cost	200€	5€

Proceeding from the key parameters, it can be concluded that the sensor produced by SICK is accurate enough. However, it is quite expensive. It should also be noted here that voltage supply is higher than the Arduino platform can provide. Consequently, the connection of this sensor will be accompanied by the introduction of additional elements into the diagram. This is not a serious problem, of course, but it will lead to additional expenses, while our task is to build a prototype at the lowest price possible.

Conclusion.

On the example of the ONOFF controller it has been ascertained that using a cheap distance sensor is not efficient. Sensors of increased precision must be used to solve this problem. However, using a more accurate distance sensor will lead to an increase in the price of the product. Hence further consideration of other control algorithms using a distance sensor is pointless.

The implementation of option 3

Algorithm 1 – OnOff.

Key elements:

- Phototransistor GL5516
- Diode 3mm 940nm

In this case it is necessary to install the sensors on one line and the desired height of the magnet. With this arrangement IR diode will create radiation, and the presence of a phototransistor fixing radiation. When you interrupt the infrared beam sensor to be determined by the location of the object. Figure 38 schematically depicts the process.

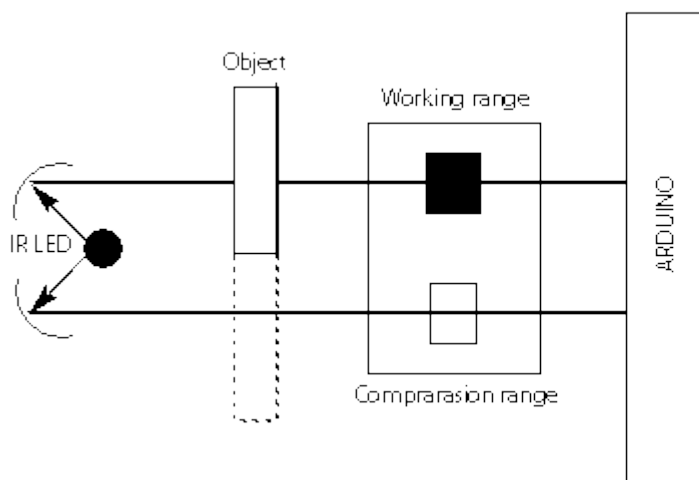


Figure 38 IR led function

Below is a diagram to the Arduino hardware platform (Figure 39).

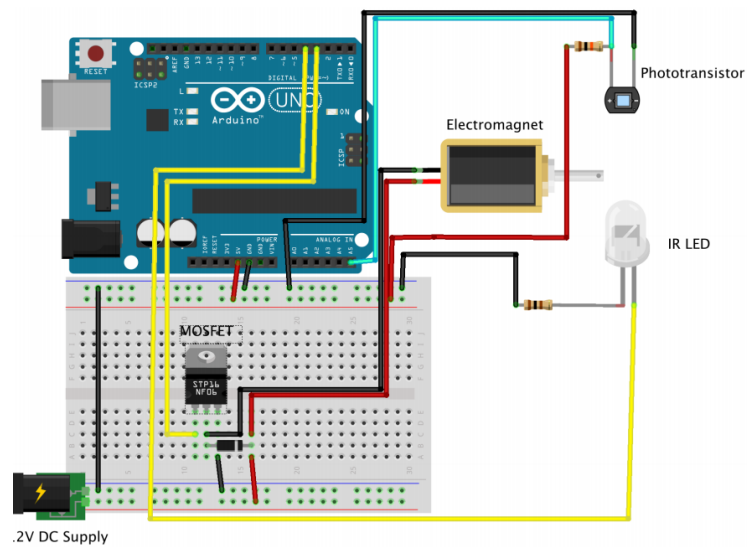


Figure 39 Connection IR System [26]

The most important problem with the use of optical elements - is the impact of external lighting. Any light falling on the phototransistor will be regarded as an input signal, which will affect the operation of the system. To prevent this, you need to be calibrated taking into account the light conditions of the room in which there is a bench.

Below is the code[25] for the control.

```
intcoilPin 11
int irPin 13
intsensorPin A0
int A =2;
int B =60;
int C =20;
int D =1000;
int maxPower =255;
long powerCountThreshold =300000;
int objectPresent =0;
int monitoring = false;
void setup()
{
  pinMode(coilPin, OUTPUT);
  pinMode(irPin, OUTPUT);
  pinMode(sensorPin, INPUT);
  Serial.begin(9600);
```

```

Serial.println("Ready");
Serial.println("m - toggle monitoring");
Serial.println("B - increase B");
Serial.println("b - decrease B");
}
void loop()
{
    static int count =0;
    static int oldPosition =0;
    static int ambient =0;
    static long powerCount =0;
    count ++;
    if(count ==1000)
    {
        ambient = readAmbient();
        count =0;
        objectPresent =(powerCount < powerCountThreshold);
        powerCount =0;
    }
    int raw =1024 - analogRead(sensorPin);
    // calibration
    int position = raw - ambient;
    // positive value means going downwards, negative going upwards
    int velocity = position - oldPosition;
    int power = position / A + velocity * B + C;
    powerCount += power;
    oldPosition = position;
    // clip
    if(power > maxPower) power = maxPower;
    if(power <0) power =0;
    checkSerial();
    if(monitored)
    {
        Serial.print(position); Serial.print(",");
        Serial.println(velocity);
    }
}

```

```
analogWrite(coilPin, power * objectPresent);  
delayMicroseconds(D);
```

```
}  
int readAmbient() //todo try speeding up delay in micros  
{  
    digitalWrite(irPin, LOW);  
    // allow timefor LED and phototransistor to settle  
    delayMicroseconds(100);  
    int ambient =1024 - analogRead(sensorPin);  
    digitalWrite(irPin, HIGH);  
    return ambient;  
}  
void checkSerial()  
{  
    if(Serial.available())  
    {  
        char ch = Serial.read();  
        if(ch =='m')  
        {  
            monitoring =! monitoring;  
        }  
        if(ch =='B')  
        {  
            B +=5;  
            Serial.println(B);  
        }  
        if(ch =='b')  
        {  
            B -=5;  
            Serial.println(B);  
        }  
    }  
}
```

As a result, we have a sufficiently stable system. However, there is a disadvantage - extraneous light sources. With a slight change in light conditions, the system becomes unstable.

Algorithm 2 - PID MATLAB.

When operating with infrared radiation, it is also possible for the control PID controller. In this case, we need to at least reduce or increase the light sensor will be determined by the location of the object. In this variant, the control will use MATLAB to control the system.

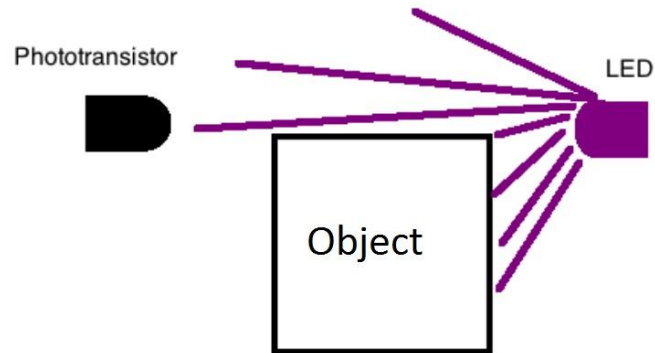


Figure 40 IR [26]

The control program written in MATLAB will be used from the command Support Package, to read voltage from the Arduino pins. The voltage values are downloaded directly to MATLAB, with reference to time. These data are displayed on a graph and analyzed in real-time to detect motion.

The code uses a combination of algorithms for motion detection, but there are many other machine learning algorithms and data analysis that can be used in such projects.

As long as the motion detector works, MATLAB software stores all the readings together with the voltage corresponding timestamps. This allows the user to process a full set of data in MATLAB after the recording is completed.

To connect the Arduino to MATLAB, you must install the MATLAB package for Arduino. This support package is available for the MATLAB, starting with R2014a release (current R2015a) and later, and is placed with the help of the installer support packages. This installer can be opened from the MATLAB line (Add-Ons -> Get Hardware Support Packages) or from the command line using the command supportPackageInstaller. After installing the support package can be connected to the Arduino.

Procedure:

- Connect the Arduino to your computer using a USB cable.
- In MATLAB, initialize the object Arduino:

```
% Inputs: Port ID (from your computer), Arduino board type  
myArduino = arduino('COM4','mega');
```

The next step is to test the scheme in order to make sure that the photoresistor responds correctly to the changing illumination.

The code below [\[27\]](#) shows how to configure the Arduino and get a voltage reading from the photo resistor via the analog output of Arduino.

```
//configure Arduino  
sens = A0;  
myarduino.configureanalogPin(sens,'Input');  
  
//Initialize variables  
readings = 750; //this should take 20–30 seconds  
times = zeros (readings,1);  
analogVoltageIn = zeros (readings,1);  
  
//Initialize a figure and Axes  
figure;  
hold on;  
ylim([0, 5]);  
titles "Analog Voltage vs. Time";  
ylabel ("Analog Voltage (Volts).");  
xlabel ("Time (seconds)");
```

```
scatterPlot - scatter (NaN(readings,1), NaN(readings, 1), 200, ".k");
```

```
//Record and Display the Analog voltage Readings in Real-Time
```

```
tic;
```

```
for r = 1:readings
```

```
    times(r) - toc;
```

```
    analogVoltageIn(r) = myArduino.readVoltage(sens);
```

```
    scatterPlot.XData(r) = times(r);
```

```
    scatterPlot.YData(r) = analogVoltageIn(r);
```

```
end
```

We will switch on and off further IR diode to see how the photo resistor reacts to illumination's changes (figure 41).

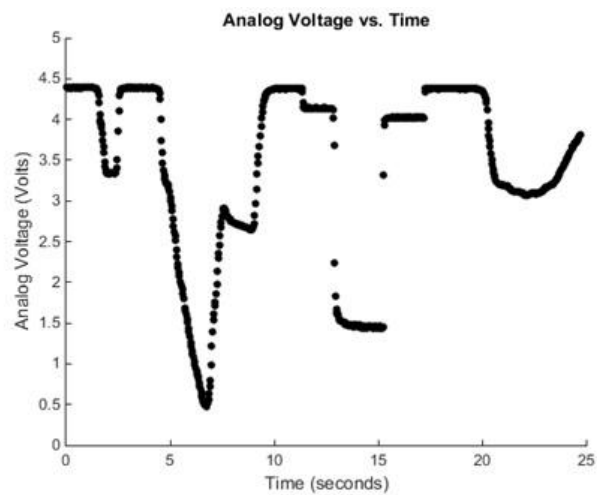


Figure 41 Check of the Photoresistor [28]

SettingPID

For the PID control in the environment of MATLAB, it is possible to use the available example of management of system of a magnetic levitation. This example is stored in MATLAB library and is available to general use (figure 42).

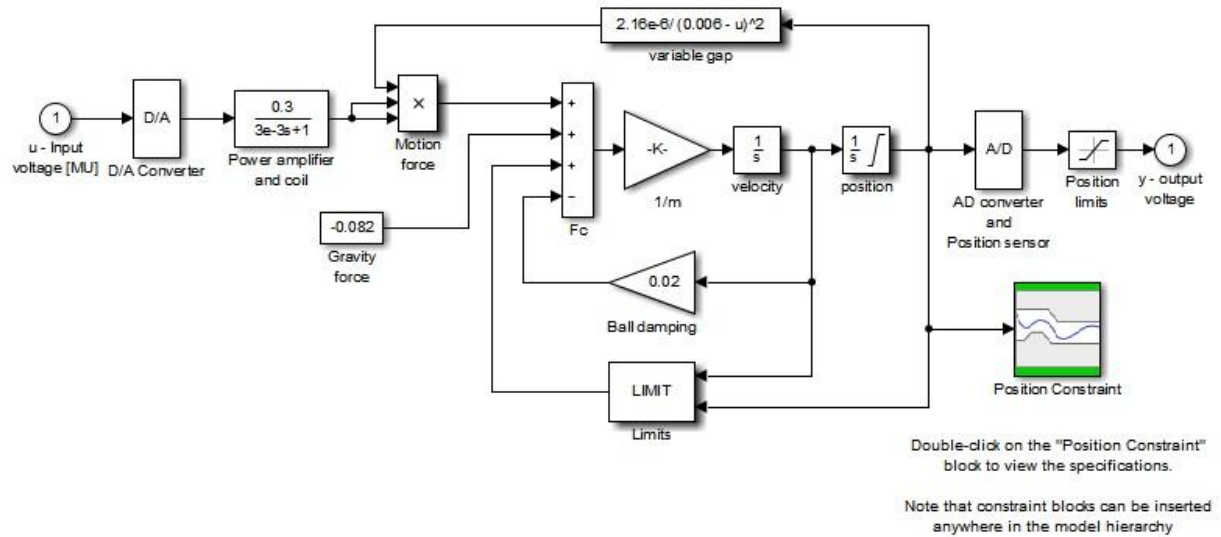


Figure 42 PID model control [29]

This example is calculated on use of object weighing 0.00837 kg. The mass of our object is other and in this regard it is necessary to carry out new settings. Having made a number of experiments, it was succeeded to stabilize system. Below the diagram of management (figure 43) is provided.

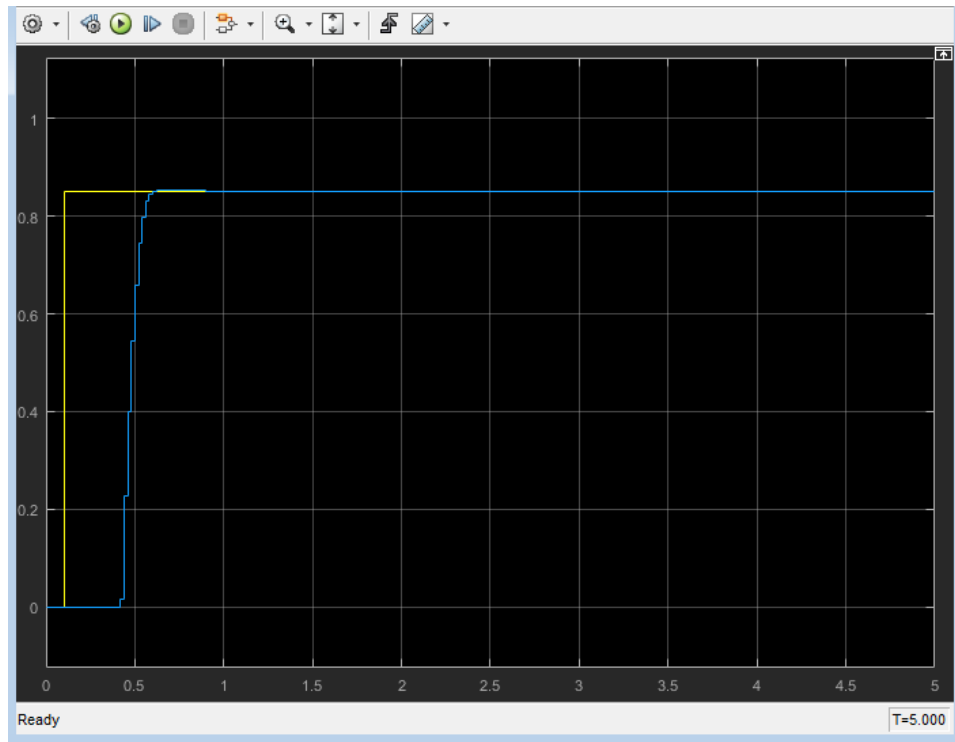


Figure 43 PID control scope [29]

Table 9 Prototype 3 cost

ArduinoMega 2560	35€
Phototransistor GL5516	2.5€
Diode 3mm 940nm	2.5€
Magnet	20€
Wire connection	5€
Frame	20€
Driver	10€
Итого	95€

The following costs were not taken into account:

- Work on the design
- The cost of the computer from which you control (in the case of the algorithm 2)
- Matlab license and necessary additions

Conclusion

This control option is operational, but the efficiency falls as a result the susceptibility to the external light sources. Optical sensors have high precision, and with it the sensitivity to errors.

The implementation of option 4

Algorithm 1 Labview

Key elements:

- OV5642 Camera module

Installing the camera module as follows (figure 44):

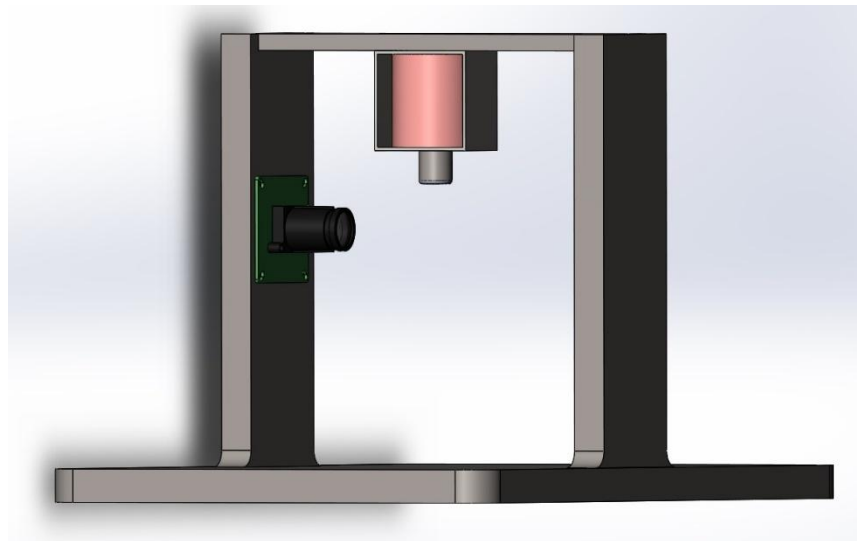


Figure 44 Camera installation

Make connections according to the diagram depicted in Figure 26, you must create a program capable of managing the system. For this LabVIEW software is used. This software is able to control the system itself through special external devices, among which there is Arduino - LabVIEW Interface for Arduino. Also create the necessary script in the NI Vision environment possibility of further transformation of the programming language C. This option does not require the use of external control, in our case - a personal computer. This method is more suitable for the final product. Since the work is aimed at defining a simpler and effective management, and involves a large number of experiments, it will be better to use the Labview environment for system control.

To get started with Arduino in LabView, you need to program our controller by sketch LIFA_Base.ino, taken from Labview folder. Also there can be found a few sketches - LabVIEWInterface.ino and LIFA_Base.ino. The first contains a description of all the functions for working with the Arduino, the second is short and collect all the pieces together for loading into the controller.

After all the necessary connections and settings, check the Arduino platform performance using LabVIEW environment management (Figure 45).

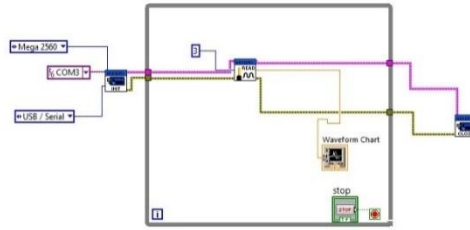


Figure 45 Labview example of program[30]

Script

Setting up the camera and took a few pictures, you can begin creating your script. Downloading the image to the environment NI Vision it is necessary to conduct a series of transformations to obtain the most beneficial shape of the image. The following figure 46 shows the conversion process of the image.

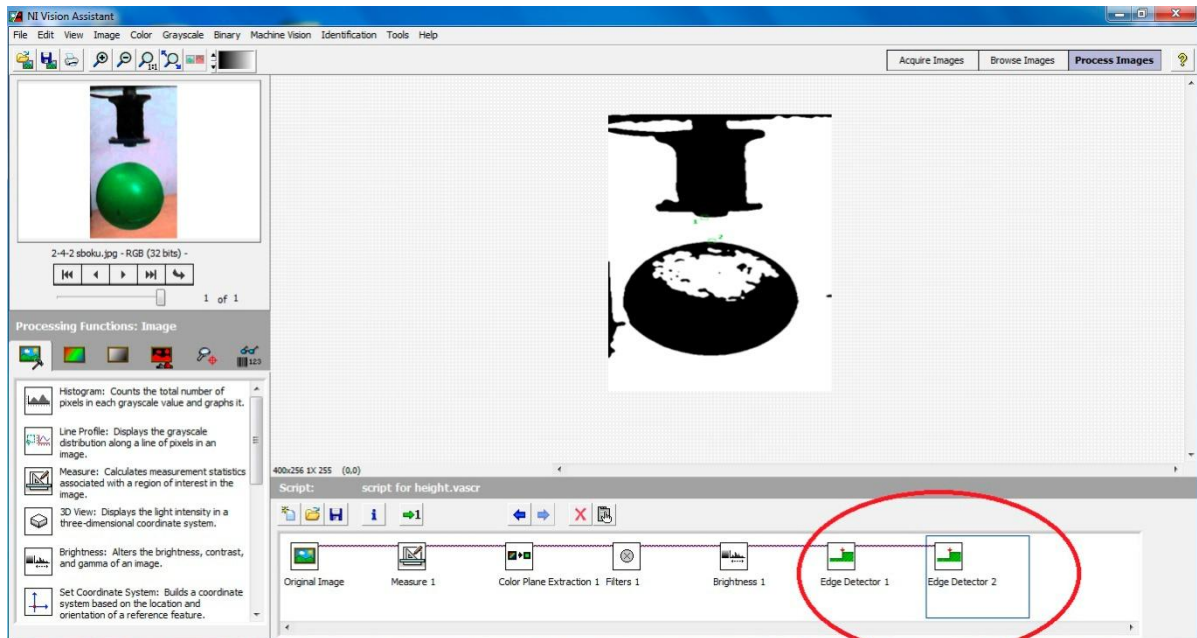


Figure 46 Ni vision

The first thing you need to do with the image is to convert it to black and white. So it will be easier to determine the position of the object. Using the required filters, we have a picture, as in figure 46. Next, using the tool Edge detector, we define the distance in pixels to the magnet and the ball. By computing the difference, we get the distance between them. This distance will be the main output value of the received script.

After integration of this script in the working environment Labview, was created the algorithm of work of system on the example code from the version control No. 1. This code is most suitable for implementation in a production environment Labview. Next, start the system, it became clear that all stages of the algorithm work, however, the system is unstable.

Table 10 The cost of the prototype 4

ArduinoMega 2560	35€
OV5642 Camera module	40€
Magnet	20€
Wire connections	5€
Frame	20€
Driver	10€
Total	130€

In total value were not taken into account:

- Work on the design
- The cost of the computer for process control
- Licence of Labview and necessary add-ons

Conclusion

Implementation of this method is not possible due to a small data rate from the camera. Given all the configuration steps, we can say that this method is much more difficult earlier. By paying attention to the price, also it shows that the price will be too high. Of course, speaking about the final decision, can be excluded from the list of your computer, it will lower the price a bit. Ultimately, should refuse this option.

Final product

At design the most important elements of a design will be considered. Considering all made experiments, for this device the Algorithm 2 – PID regulator has been chosen from option of management No. 1 as the main algorithm. It follows from this that the holder for a magnet can have only one point of support. It will facilitate a design and will give considerably bigger viewing angle. Also, it is necessary to consider 2 sensors of the Hall and to design fastenings for them. Characteristics of a magnet won't be considered, and the sizes are chosen conditionally on the basis of data from a prototype.

Design

As a basis was one of prototypes working by the same principle is taken. The sketch of the device (figure 47) is given below.

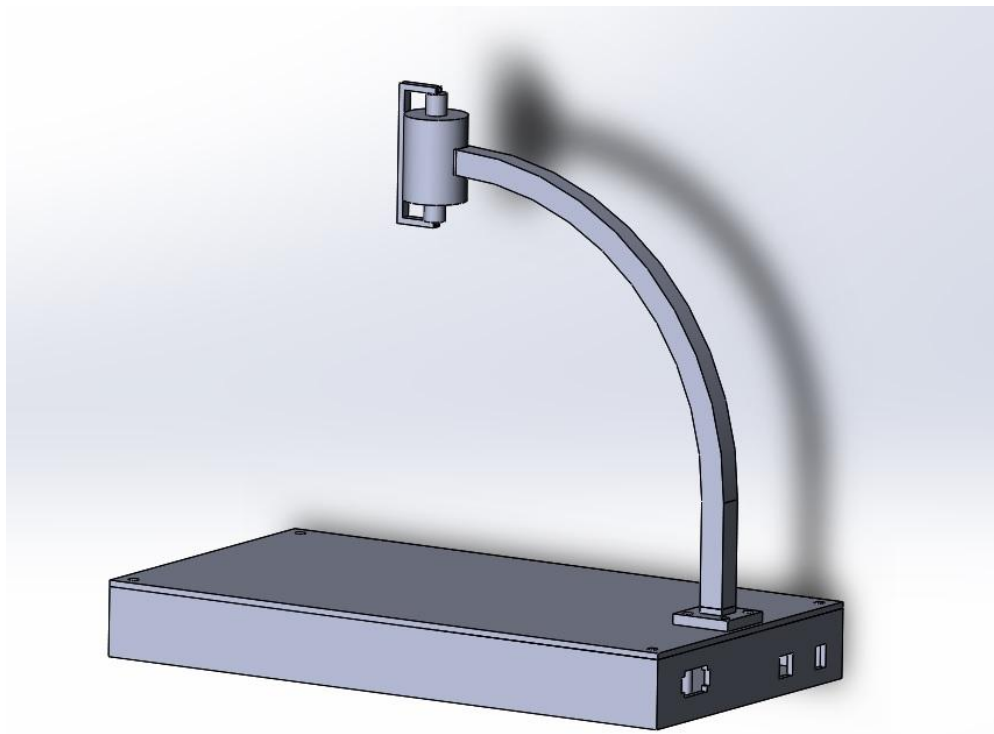


Figure 47 3D Model

Platform

The platform will have the sizes for placement in it all necessary elements:

- Arduino platform
- Power supply unit
- Driver
- C8 for 220V 0721-PS (figure 48)



Figure 48 0721-PS [30]

Figure 49 shows a schematic layout of all components within the platform.



Figure 49 Platform inside view

In the production of all elements of the body used plastic fifth group - Polypropylene. Unlike polyethylene, polypropylene, a less dense (density 0.91 g / cc, which is generally the lowest value for all plastics), a hard (abrasion resistant), a heat-resistant (begins to soften at 140 ° C, melting point 175 ° C) hardly undergoes corrosion cracking. Has a high sensitivity to light and oxygen (sensitivity decreases when administered stabilizers). The use of this type of plastic to reduce weight of the structure. The price of material and its treatment is not high, which makes the product cheap to manufacture.

Comparison with Inteco Maglev

Table 11 Comparison

	Inteco Maglev	Our Device
Weight	≈20kg	≈5kg
Dimensions	450x380x530 mm	300x160x270
Supply voltage	220v	220V
PC requirement	YES	NO
Price	3500€	<200

Calculation of cost was made with use of the prices stated above. The price doesn't include work on design. Also retail prices were taken into consideration, cost will significantly decrease in case of use of wholesale prices.

Conclusion

As stated previously, the aim was to investigate various system management principles. The main control element was Arduino platform. The selected system of the magnetic levitation is extremely difficult to stabilize. In attempts to stabilize such a system, the advantages or disadvantages of different algorithms become apparent. It was acquired useful experience in getting acquainted with all the nuances of control systems. A possible improvement of this system - is the use of a different design. For example, by installing the magnet directly into the stand platform, thus the object is placed over the magnet. The second option - the use of two or more magnets for more precise control. This option allows to fix the position of the object in the axes x and y.

As a result, we receive a product much cheaper, than the available Inteco Maglev. From advantages It should be noted:

- Low price
- Small weight
- Simple design

Of course, It should be noted that the product of the Inteco company works with the help of the program Matlab environment. Certainly this software has huge potential and is very useful in educational process. It does this product directed to use in higher educational institutions. In the created product the Arduino platform which is "the open project" that does it by the most popular device among the beginning engineers is used. This device can be bought in any shop of electronics at the low price and to begin to do the first projects which examples lie in open access. Our product can be used as the manual not only at universities, but also in gymnasiums. Thus causing interest in mechatronics among the younger generation.

Summary

The stand installed at the Tallinn Technical University became idea for the choice of this subject for research. This stand is located at institute of automatic equipment and is a product of Inteco firm. The main objective of this stand is acquaintance of student's opportunities of control and stabilization of unstable systems. At the presentation of this stand, there was a question of application of other control algorithm and on how many it will be effective. In view of the approximate cost of this stand, the motivation has appeared to make a similar product cheaper. Having investigated the market, it became clear that as the manual isn't enough similar devices developed. Choosing this subject of research, it has been taken into account, complexity of management of this system, and it's stabilization will become a useful practice. Stabilization will be carried out by different methods. These methods include both the different software, and hardware. As the main platform of management the programmable Arduino Mega 2560 controller was used.

Main goal of work was researching of different options of management of system of a magnetic levitation. In the course of research, first of all, the main options of control algorithms have been defined:

- Algorithm 1 – Hall Sensor
- Algorithm 2 – Ultrasonic sensor of distance
- Algorithm 3 – Optical sensors
- Algorithm 4 – Camera

Key difference of each algorithm from each other is the feedback device. Platform of management is constant – Arduino Mega 2560. Further all necessary elements for system of feedback have been picked up. Also examples of a program code for each option have been given. Having investigated 4 main control algorithms, all nuances of realization of each of them became clear. For the last two algorithms the model of management has been built on the basis of the software of Matlab and Labview. Licenses to this software have been provided by the Tallinn Technical University. During research experiments with real objects were made. Practical tasks have allowed to approach realization and the analysis of each algorithm with the greatest efficiency. The prototype for experiments were made. In end of the analysis, calculation of cost of realization of each prototype has been made. On the basis of these data it was possible to draw a conclusion what method will be most favorable by production of a final product.

As a result, one method has been chosen for production of a final product. The algorithm with use of sensors of the Hall was the most effective. This choice is explained by a simple design, the low price and the main thing, immunity to external hindrances. From negative sides – an opportunity to use as object only a magnetic. Considering the main destination of this stand, this minus is insignificant.

The 3D project of a final product has been presented in the conclusion of work. The detailed analysis wasn't made, however, the main requirements to the stand have been considered and developed. In additional materials necessary drawings are added.

The main advantage of this work is research of unstable systems and a possibility of their management. Thanks to practical approach, a set of nuances of management of systems became known and clear.

Kokkuvõte

Sellise teema valimiseks lükkas mind Tallinna Tehnikaülikoolis paigaldatud stand. See stand asub Automaatikainstituudis ja toode on INTECO firma oma. Stendi peamine eesmärk on tudengitele/õpilastele tutvustada kontrolli võimalusi ja ebastabiilse süsteemi. Standi esitlusel tekkis küsimus kasutamise kohta teiste juhtimisalgoritmiga ja kui efektiivsem see on. Arvesse võttes milline standi maksmise summa võiks tulla, on motivatsioon teha sama toode aga madala hinnaga. Uurides turgu, sai selgeks, et sarnased seadmed, mis on mõeldud õppevahendina on väga vähe. Antud teemaga, on arvesse võetud keeruline süsteemi juhtimine ja selle stabiliseerimine on kasulik praktikas. Stabiliseerumine viiakse läbi erinevate meetoditega. Need meetodid hõlmavad nii erinevaid tarkvara ja riistvara. Peamine platvormi juhtimises kasutatakse programmeeritav kontrolleri Arduino Mega 2560.

Peamine eesmärk oli uuringu erinevate võimaluste süsteemi haldamise Magnet levitatsiooni seadmed. Töökäigus esimeseks sai kindlaks põhilised juhtimisalgoritme valikud:

- Algoritmi 1 - Hall Sensor
- Algoritmi 2 - Ultraheli kauguse andur
- Algoritmi 3 - Optilised andurid
- Algoritmi 4 – Kaamera

Iga algoritmi peamine erinevus üksteisest on seade tagasiside. Püsivaks jääb juhtimise platvorm - Arduino Mega 2560. Lisaks valiti kõik vajalikud elemendid tagasiside süsteemiks. Samuti on toodud näidised töökoodid iga variandi jaoks. Peale uurimist 4 põhilist juhtimisalgoritmi, sai selgeks kõik detailid igaühe elluviimise. Viimase kahe algoritmi juhtimismudel on ehitatud põhinema Matlab ja LabVIEW tarkvaraga. Selle tarkvara litsentsid on ette nähtud Tallinna Tehnikaülikooliga. Töö käigus viidi katsed reaalsete objektidega. Praktilised tööd lasid teha realiseerimise ja analüüsi iga algoritm suurima kasuteguriga. Selleks ehitati prototüüp, mille peal tehti katsed. Analüüsi lõppus tehti arvutamise, iga prototüüpi rakendamise hinna. Nende andmete põhjal saab järeldada, mis meetod oleks kõige soodsam lõpptoote tootmiseks.

Selle tagajärjel valiti üks tootmise lõpptoote. Kõige tõhusam oli algoritm Halli anduriga. See valik on põhjustatud lihtsa struktuuriga, madala hinnaga, ja mis kõige tähtsam, immuunsus välise sekkumise eest. Negatiivse külge - võime kasutada objektina ainult magnet. Võttes arvesse standipeamine eesmärk, see puudus on tühine.

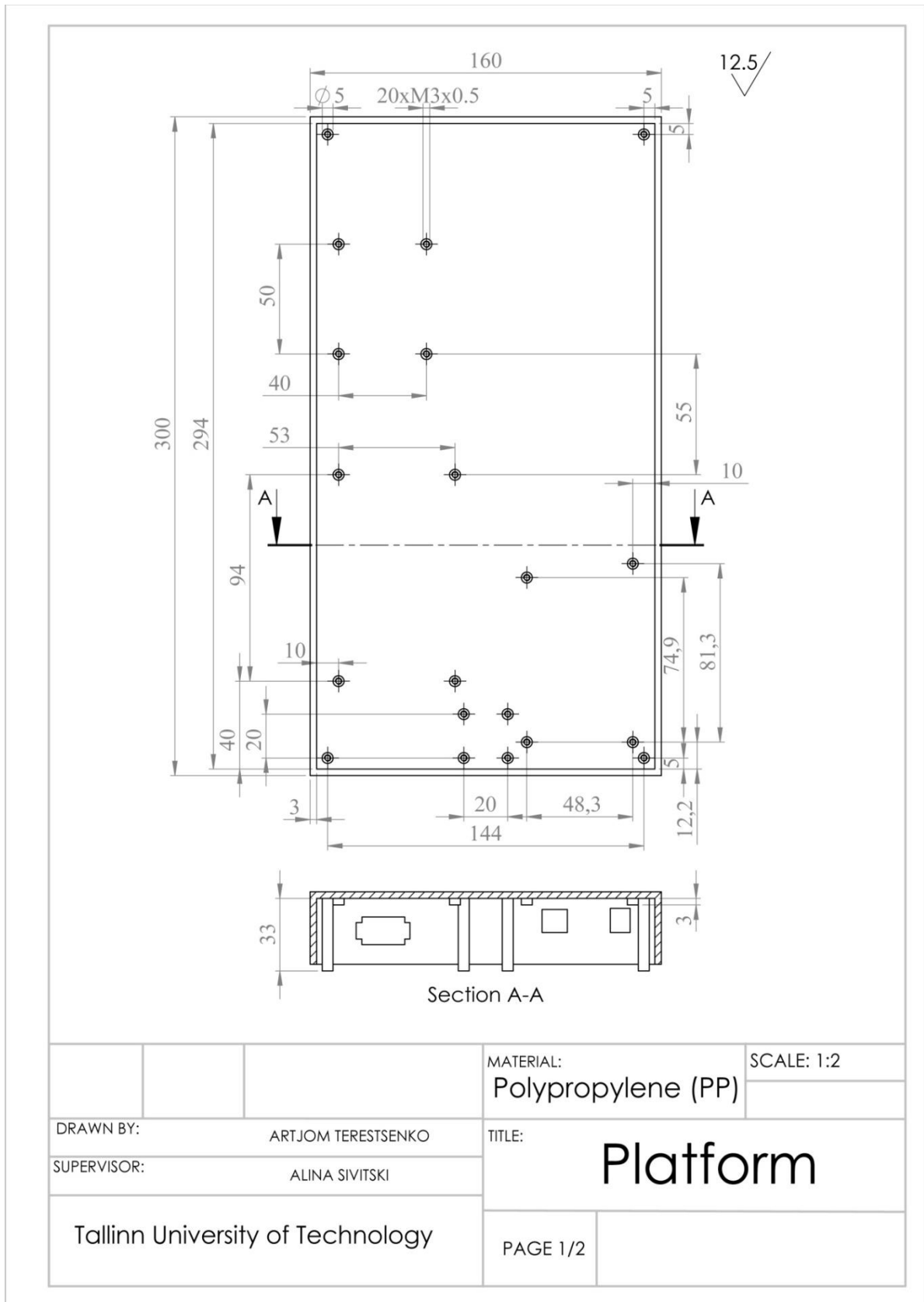
Töö kokkuvõttes esitati 3D lõpptoote projekt. Üksikasjalikku analüüsi ei ole esitatud, aga stendi põhiolemused võeti arvesse ja arendada. Majalikud joonised lisatud lisamaterjalidesse. Selle uuringu peamiseks eeliseks on uurida ebastabiilse süsteemi ja selle juhtimise võimalus. Tänu praktilise lähenemise sai teada ja mõistetavat süsteemide juhtimise nüansse.

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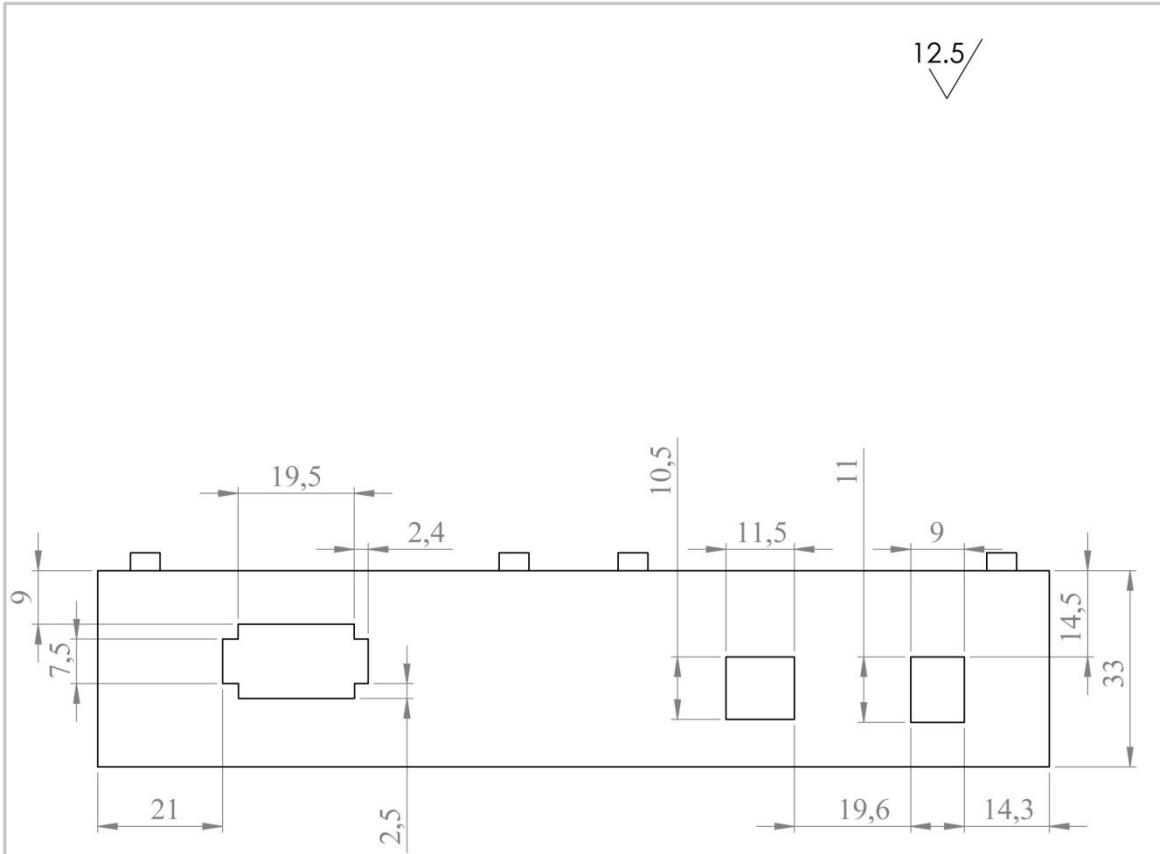
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Additions

Additional 1 - Platform drawing 1/2

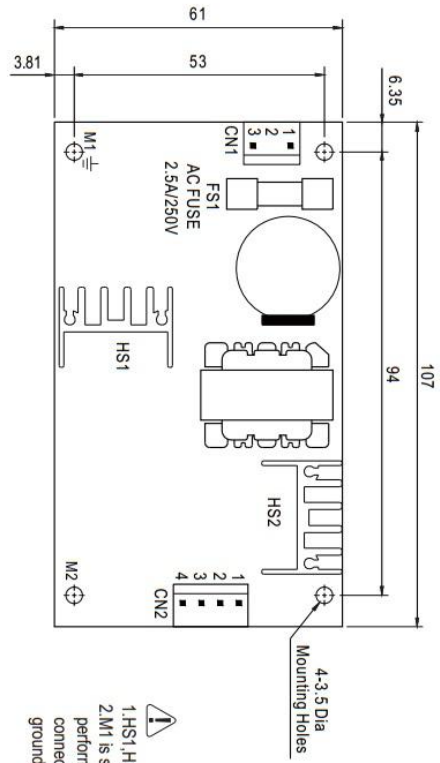


Additional 2 - Platform drawing 2/2

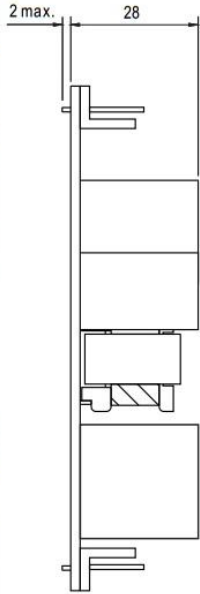


			MATERIAL: Polypropylene (PP)	SCALE: 1:1
DRAWN BY: ARTJOM TERESTSENKO		TITLE: Platform		
SUPERVISOR: ALINA SIVITSKI				
Tallinn University of Technology		PAGE 2/2		

Additional 3 - AC DC Converter drawing



- ⚠
1. HS1, HS2 cannot be shorted.
 2. M1 is safety ground. For better EMC performance, Please secure an electrical connection between M1, M2 and chassis grounding.



AC Input Connector (CN1) : Molex 41791-03 or equivalent

Pin No.	Assignment	Mating Housing	Terminal
1	AC/L	Molex 2139 or equivalent	Molex 2478 or equivalent
2	No Pin		
3	AC/N		

DC Output Connector (CN2) : Molex 41791-04 or equivalent

Pin No.	Assignment	Mating Housing	Terminal
1,2	+V	Molex 2139 or equivalent	Molex 2478 or equivalent
3,4	-V		

⚡ : Grounding Required