ZÁPADOČESKÁ UNIVERZITA V PLZNI
FAKULTA ELEKTROTECHNICKÁ

KATEDRA APLIKOVANÉ ELEKTRONIKY A TELEKOMUNIKACÍ

DIPLOMOVÁ PRÁCE

Návrh, analýza a aplikace řízení aktuátoru hmatové zpětné vazby a systému snímání tlaku pro dotykové vstupní zařízení v automobilu

Bc. Miroslav Svoboda 2018

ZÁPADOČESKÁ UNIVERZITA V PLZNI
Fakulta elektrotechnická
Akademický rok: **2017/2018**

ZADÁNÍ DIPLOMOVÉ PRÁCE

(PROJEKTU, UMĚLECKÉHO DÍLA, UMĚLECKÉHO VÝKONU)

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Studijní obor:	**Dopravní elektroinženýrství a autoelektronika**
Název tématu:	**Návrh, analýza a aplikace řízení aktuátoru hmatové zpětné vazby a systému snímání tlaku pro dotykové vstupní zařízení v automobilu**
Zadávající katedra:	**Katedra aplikované elektroniky a telekomunikací**

Zásady pro vypracování:

1. Proveďte návrh obvodu, signálovou analýzu a simulaci pro systém buzení cívky, intenzitu indukovaného magnetického pole a indukční proudy pro snímání tlakové síly. (Circuit calculation, signal analysis and simulation for coil driving circuitry and induced magnet field strength, induction currents for force sensing.)

2. Proveďte návrh obvodu, analýzu "worst case" a návrh desky plošných spojů pro systém aktuátoru s hmatovou zpětnou vazbou a systém vyhodnocení tlakové zpětné vazby. (Circuit design, worst case analysis and layout for haptic feedback actuator circuitry, force feedback evaluation circuitry.)

3. Zhotovte prototypovou desku včetně softwaru pro základní řízení pro předváděcí a měřicí účely. (Build up of a prototype board including basic control software for demonstration and measurement purpose.)

Rozsah grafických prací:	**podle doporučení vedoucího**
Rozsah kvalifikační práce:	**40 - 60 stran**
Forma zpracování diplomové práce:	**tištěná/elektronická**

Seznam odborné literatury:

Student si vhodnou literaturu vyhledá v dostupných pramenech podle doporučení vedoucího práce.

Vedoucí diplomové práce:	**Ing. Jan Mráz, Ph.D.**
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Datum zadání diplomové práce:	**10. října 2017**
Termín odevzdání diplomové práce:	**24. května 2018**

L.S.

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děkan

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Abstrakt

V této diplomové práci psané v angličtině byla spočítána, nasimulována a následně navržena elektrická část aktuátoru pro hmatovou zpětnou vazbu. Dále byly odsimulovány řídící a měřící obvody a následně byla navrhnuta deska plošných spojů. Na tento hardware byl vyhotoven software. Aktuátor je typu voice coil. Při stisku tlačítka se v cívce indukuje napětí, které je změřeno a následně zesíleno. Na základě této hodnoty, která se dostane na A/D převodník procesoru, je řízen H-můstek a je spínán tak rychle, že aktuátor vydává vibraci. Tato vibrace je následně předána uživateli přes dotykovou plochu. V poslední kapitole byla věnována pozornost především softwaru a následné interakci s hardwarem a mechanickou částí aktuátoru. Byla navržena vylepšení pro vývoj další verze haptického demonstrátoru.

ABSTRACT

In this diploma work written in English, the electric part of an actuator for haptic feedback has been calculated, simulated and subsequently designed. Furthermore, control and measurement circuits were simulated and a printed circuit board was then designed. This software has been developed for this hardware. The actuator is a type of voice coil, where the voltage is induced with a press of a button. This voltage is measured and then amplified. Based on this value, which is received by the processor's A/D converter, the H-bridge is controlled and switches so quickly that the actuator emits a vibration, which is then transmitted to the user via the touchpad. In the last chapter, attention was paid mainly to the software, but also to the subsequent interaction with the hardware and the mechanical part of the actuator and their debugging. Improvements have also been proposed to the development of new version of the haptic demonstrator.

KEY WORDS

Voice coil actuator, H-bridge, finite element simulation, haptic feedback, tactile, perception, measuring circuitry, static part, moving part, equivalent circuit, force feedback,

Prohlášení

Prohlašuji, že jsem tuto diplomovou práci vypracoval samostatně, s použitím odborné literatury a pramenů uvedených v seznamu, který je součástí této diplomové práce.

Dále prohlašuji, že veškerý software, použitý při řešení této diplomové práce, je legální.

....

podpis

V Plzni dne 22.5.2018 Miroslav Svoboda

Acknowledgment

I would first like to thank Ing. Jan Mráz Ph.D. for professional and factual comments, willingness, and patience during the consultation of this work.

Second I would like to thank my thesis consultants in company Continental Engineering Services, Christoffer Grahl, Jasmin Yousef, and Octavian Ghermann for their willingness and practical advice. Whenever I ran into a trouble spot or had a question about my research or writing. They consistently allowed this paper to be my own work but steered me in the right the direction whenever they thought I needed it.

Finally, I must express my very profound gratitude to my parents, sisters and my girlfriend for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

Content

List of symbols and abbreviation

PCB - printed circuit board

VCA - voice coil actuator

LRA - linear resonant actuator

ERM - eccentric rotating mass actuator

ADC - analog digital converter

DAC - digital analog converter

PWM - pulse width modulation

SMD - surface mount device

THT - trough hole technology

IC - integrated circuit

VCC - battery supply

BOM - bill of material

Introduction

Significant technological advances often bring major changes in society as it has been in the past. Nowadays we live in the 21st century and on a planet, there are 7.5 billion of people and most of them need to transport themselves every day, therefore cars play a big role in human´s life. People spend lots of time in cars, therefore a development of better car systems is needed because it can make the driving less difficult. Cars are way different than they were 50 years ago. They are full of electronics assistants in order to make driving much easier and comfortable and also due to a safety and efficiency. Due to the constant adding of new assistants, one can almost not drive at all and only sit. Autonomous driving is not so far future but it has still lots of problems, that needs to be taken care of. And the idea something drive for you does not like everyone. Nevertheless, lots of assistants such as head-up displays, line assistant, automatic braking of a car can save lots of lives. Because of the customer needs and car's manufacturer competition, there is a need for safe handling car systems like touch radio or GPS. Almost every car manufactured in the year 2018 has a couple of displays. In order to control these displays safely, a haptic feedback is a very good idea so that the driver can focus on the driving itself.

On the beginning of my thesis, a definition of haptic is described, a block diagram is created, then some other principles are introduced, which are necessary to understand the whole concept of a product of this master thesis - haptic demonstrator. The aim of my thesis was to develop this demonstrator so that the device can be later used in a car. It will consist of an actuator and driving and sensing circuitry. The actuator is meant to be in a car behind a display. One can recognize that the button or small display is pressed because it gives a feedback in form of vibration so that someone must not have a look at the button while driving due to the safety. This feedback is done by voice coil actuator. From a sensing circuitry processor recognizes, that button is pressed and it starts to drive the actuator over a H-bridge. Furthermore, all necessary calculations, simulations, PCB, and software design are described.

I chose this topic because it is very interesting for me. This project is a complex and diverse and I will enjoy both, fist to study necessary theory and then apply it in a practical part. Another great motivation for me is, that this master thesis is done for a company called Continental Engineering Services located in Regensburg and this company could use this or next generation of this device in a real application. I commuted to Regensburg usually two times in a week for consultation and to do a major practical part of my thesis.

2 Design of haptic feedback actuator

To design a haptic feedback actuator is necessary to know what the word haptic means. Haptics is derived from a Greek term “haptios” and described as “something that can be touched”

Meaning haptics has changed many times in a history. Nowadays haptics can be described according to [1]. It means the combined sensation of mechanical, thermal and nociperception s can be seen in a Fig. 1. In other words, haptics is more or less defined by the exclusion of the optic, acoustic, olfactory and gustatory perception from the sum of sensory perceptions. From above mentioned can be determined that a haptic device is a system for generating an output which can be perceived haptically.

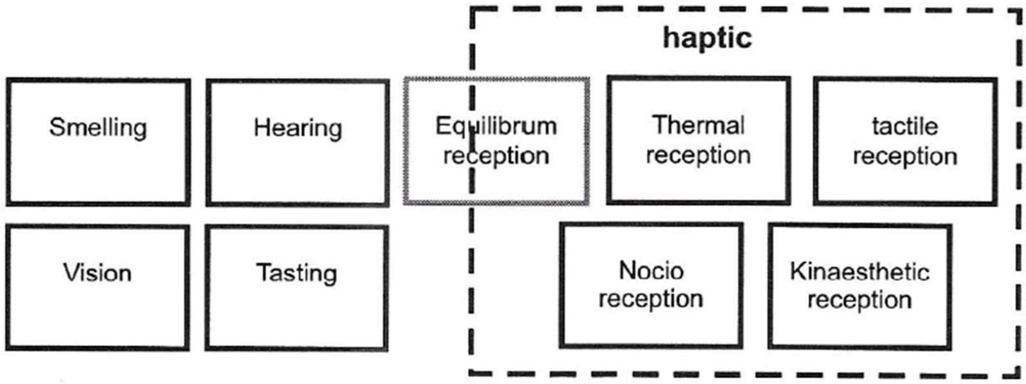


Fig. 1 Distribution of senses [1]

Tactile means the mechanical interaction with the skin. Therefore, tactile perception is the sensation of exclusively mechanical interaction. Tactile feedback technology then uses a person’s sense of a touch to provide feedback by applying forces, vibrations, or motion to the user. A simple example of haptics technology is a well-known vibration alert used in mobile phones and tablets. [1]

Nowadays there is a trend to have displays or a touch button in many applications. One can replace a mechanical button with a tactile feedback button for example, a mechanical light switch in a car. It is done mostly because of a customer`s desires and in order to keep up with competitors. When touch buttons and displays are used a tactile feedback is a very good idea in order to recognize that some button was really pressed. It is a safety measure because a driver should focus on driving.

2.1 Types of vibration actuators

According to the [1] there is a big number of actuators, which are using different actuating principles. Most common principles for use in a haptic application are: electrodynamic, electromagnetic, piezoelectric and capacitive. In order to determinate which actuator will be best for this application some of the most common actuators are mentioned.

2.1.1 Eccentric Rotating Mass (ERM) actuator

ERM is a DC motor which is working on a simple principle that on a shaft is attached an unbalanced mass. Because the motor is attached to some device, the motor displacement results in the vibration of the entire device. The input to the ERM motor is a DC voltage. The input voltage of an ERM motor ranges from 1 to 10 V, and the operating current ranges from 130 to 160 mA. The frequency of operation ranges is from 90 to 200 Hz. ERM motors are cheap and provide strong vibrations, however, they have a too long response time (40-80 ms) and therefore are not suitable for high-quality haptic feedback. Vibration alerts in mobile phones would be a typical example of this actuator. [2]

2.1.2 Piezoelectric actuators

An inverse piezoelectric effect is used in this type of actuator. A Piezoelectric crystal is deformed when a voltage is applied. This physical deformation generates vibrations in order to provide a touch feedback. Piezoelectric actuators are manufactured from ceramic materials. The input voltage to the piezoelectric actuator is a sine wave. The operating voltage of a piezoelectric actuator is in a range from 50 -200 V and the instantaneous current can be up to 300 mA. The operating frequency of piezoelectric actuators is in ranges from 150 to 300 Hz. These actuators are lightweight, have a thin form factor, and provide a very fast response time (< 1ms). That is the reason why they are suitable for providing high-quality haptics effects in mobile phones and tablets. [2]

2.1.3 Linear Resonant actuators (LRA)

The LRA is made of a movable mass, permanent magnet, voice coil and springs as shown in Fig. 2. When a sinusoidal input is applied to the voice coil, it produces a magnetic field that interacts with the permanent magnet, causing it to move linearly. Movable mass is pushed up and down by a permanent magnet, which results in vibrations. The spring is attached to the movable mass in order to bring the magnet back to its initial position. The input to LRAs is usually a sine wave. The operating voltage of LRAs is in a range from 2.5 V to 10 V, and the operating current ranges from 65-70 mA. The typical operating frequency (resonant frequency) of an LRA motor is 175 Hz. LRAs have a faster response time (20-30 ms) compared to ERMs and are capable of providing more precise and softer vibrations. LRAs are commonly used in smartphones to provide a touch feedback while typing keys on the virtual keypad. [2]

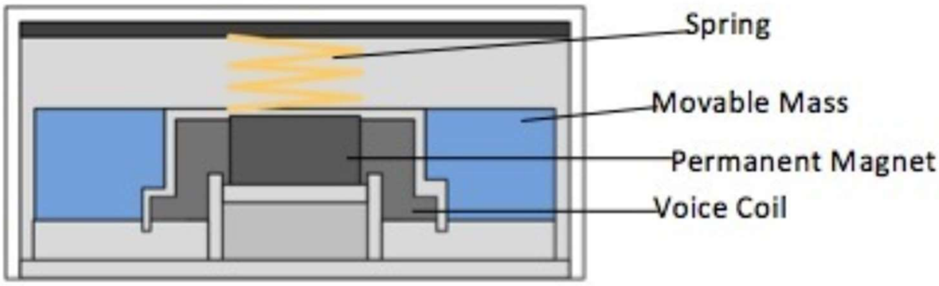


Fig. 2 LRA actuator construction [2]

2.1.4 Voice coil actuator VCA

In a [3,4] is written, that the Voice coil actuators are direct drive devices with limited motion. VCAs are non-commutated electromagnetic devices. They are used in applications that require linear force. This actuator works on a principle of a Lorentz force, which is proportional to the product of the magnetic field and the current, in a direction perpendicular to both of them. Magnetic field strength is constant, as with a permanent magnet, the magnitude of the force it exerts on the wire is proportional to the magnitude of the current through the wire. Lorentz force is the combination of electric and magnetic force on a point charge due to electromagnetic fields. An elementary charge q moving with velocity v in the presence of an electric field E and a magnetic field B experiences a force. This type of actuator is chosen for the use in the haptic demonstrator, because of the simplicity of the construction and possibility of changing output force only with adjustment of a current.

Construction of VCA

Mechanical properties of VCA match to the characteristics of classical loudspeaker that transmits electrical signal on the mechanical movement, most commonly cylindrical coil.

Voice coil actuator consist of soft iron, coil, coil holder and permanent magnet as can be seen in a Fig. 3. The electrical part of the VCA is formed by coil wound on the coil holder. The coil is wound with a copper coated conductor. Copper is selected due to the low resistivity value. The coating on the conductor surface serves as insulation to avoid conductor joining in the individual layers of the coil.

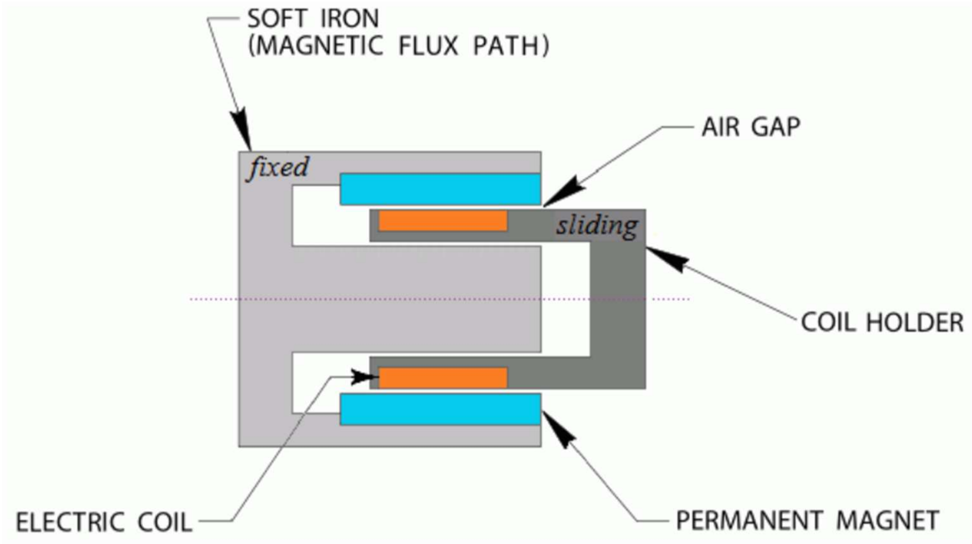


Fig. 3 Components of voice coil actuator [5]

2.2 Block diagram

In order to understand what all will be needed to build this haptic demonstrator, a block diagram had to be created. According to [2] haptic feedback devices have following parts:

Touch Interface: The touch interface is the area where the user interacts with the system. It can contain sensors that are touch sensitive. The touch interface can be a touch screen, touch button, or both.

Touch Sensing controller/ Touch sensing circuitry: The touch sensing controller detects a finger touch or the location of a finger touch on the touch surface. In the case of a touchscreen, the touch controller sends the touch coordinates to the application processor for processing. In the case of touch buttons, the touch controller sends the ON/OFF status to the application processor. In case of my thesis, there will be a sensing circuitry, which will sense induced voltage inside of the actuator.

Haptics processor: The Haptics processor consists of control software and algorithms that generate the haptics waveforms required to drive an actuator. The Haptics processor can be implemented as integrated with application processor or standalone processor or integrated with touch controller or integrated with an actuator driver IC.

Actuator: The actuator is an electro-mechanical component used to generate vibrations and provide a touch feedback to the user. The haptics processor provides the input to the actuator. The actuator will be integrated with the touch user interface so that it vibrates the device when the input is applied to the actuator.

2.2.1 Basic description of a function of a haptic demonstrator

Working principle of haptic feedback demonstrator will be described step by step in order to understand how it works and can be seen in a Fig. 4.

1. User pressed a button/ surface of a haptic demonstrator
2. When a button is pressed, the coil in an actuator is moved and inside of the coil is a voltage induced
3. Induced voltage is measured by a sensing circuitry and amplified
4. This amplified voltage gets to the ADC of the processor
5. Based on the signal from the ADC processor drives a H-bridge using PWM
6. H-bridge deliver energy into actuator, according to the setting in a software. Software is done in order to gain the best haptic feedback
7. Vibration is forwarded into a touch interface
8. Over the touch interface is the haptic feedback given to the user

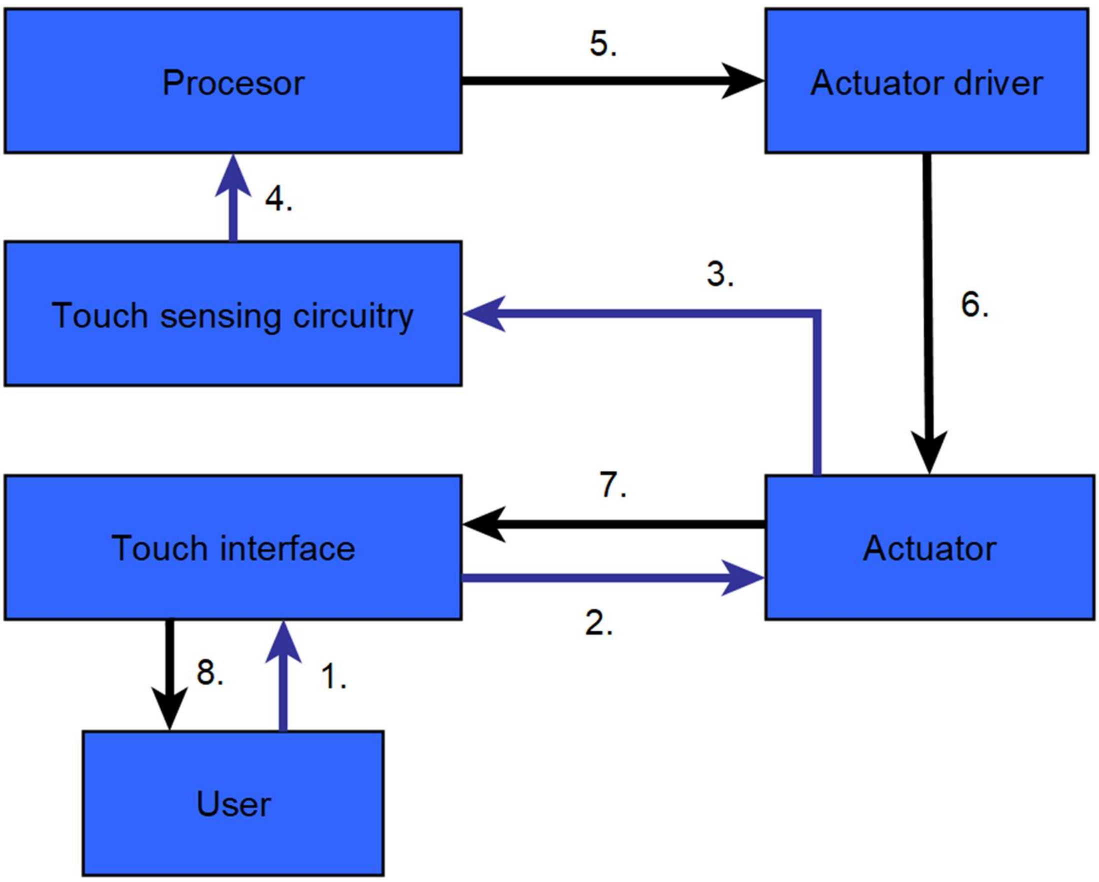


Fig. 4 Haptics system block diagram

2.3 Design and calculation of electric parts of a Voice coil actuator

Voice coil actuator is an electrodynamic actuator. According to [1] electrodynamic actuators are most frequently used type of drives for haptic applications. This popularity is a result of the direct proportion between their output (force in VCA case) from their input values (the electrical current). They are used for tactile applications because these actuators are very dynamic and they are very frequently applied for oscillating excitements of skin areas. In the Fig. 5 is described electromagnetic circuit of a Voice coil actuator. Two systems exist, one with moving coil and one with moving magnet.

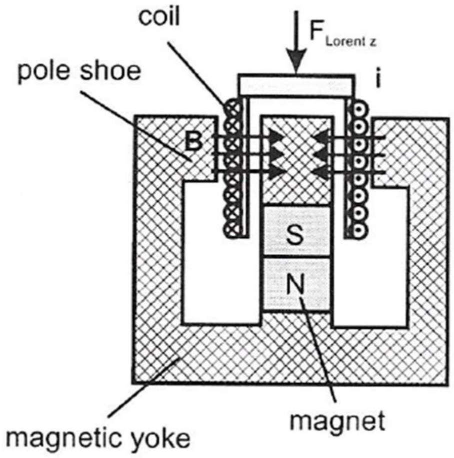


Fig. 5 Moving coil actuator magnetic schematic [1]

Calculation of a wire size and a number of windings was done tightly together with a simulation of a magnetic field (Chap. 2.4.4) because a Lorentz force was simulated based on calculated data and the calculation was changed so that a force acting upon the coil has required value.

2.3.1 Calculation of a flux density in the air gap

In order to calculate Lorentz force a magnetic flux density in the air gap is needed, although this calculation is only approximate and it can be calculated only with some assumptions. In the H-B diagram, the magnetic flux density in the air gap is determined by the intersection of the demagnetization curve of the permanent magnet with the load line of the attached magnetic circuit as shown in Fig 6. High currents leading to a demagnetization field Hd and temperatures may shift the demagnetization curve to the right reducing the magnetic field in the air gap at the equilibrium position. Therefore a NdFeB magnet is chosen that has the highest currently available magnetic energy. The magnitude of an air gap significantly influences resulting density of magnetic flux in the air gap. [6]

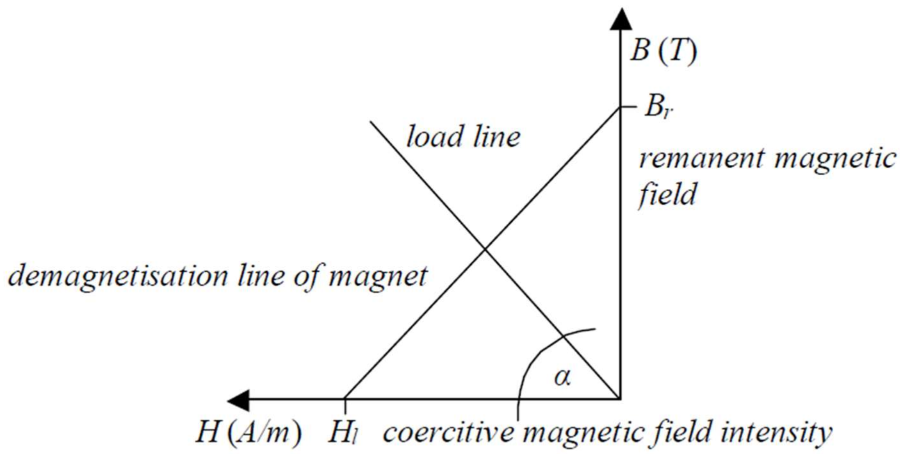


Fig. 6. Simplified B-H characteristics for the calculation and its intersection with a load line [6]

For calculation of magnetic flux density in the air gap, an equivalent circuit is needed. In the Fig. 7 a) and b) is an equivalent circuit described. Two approaches for a calculation has been used in order to validate the results.

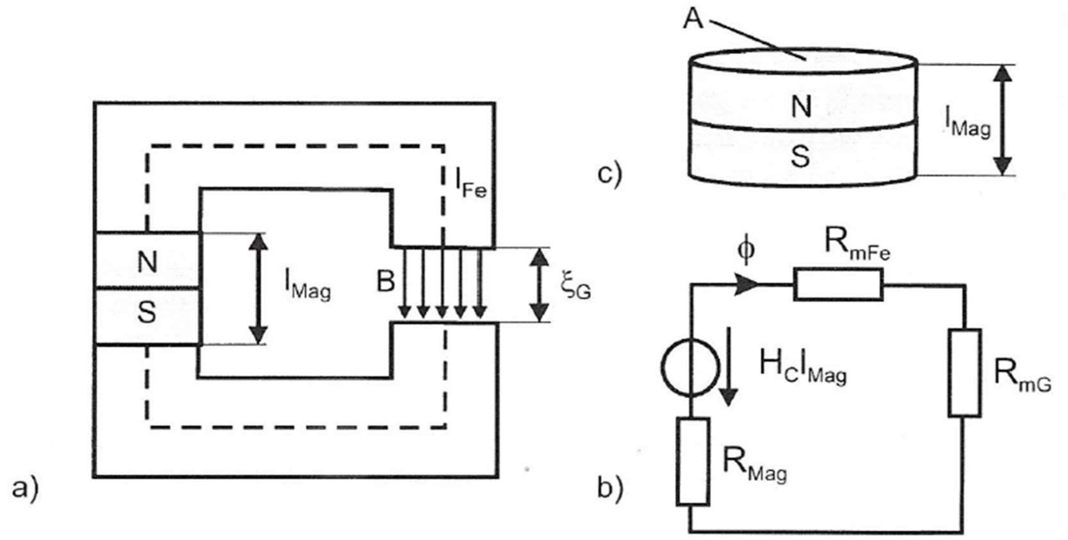


Fig. 7 Magnetic field generation B via permanent magnets a), derived equivalent circuit b), and dimensions of the magnet c) [1]

Calculation of demagnetizing factor

According to the [7] first Maxwell equation can be used:

$$\oint H\,dl = H_{mag}\,l_{mag} + H_{Fe}l_{Fe} + H_{air}\delta_{air} \tag{2.1}$$

For the calculation is necessary that a magnetic field strength in iron is neglected. We use following assumption $\mu_0 \rightarrow \infty => H_{Fe} = 0$ and we get

$$H_{air} = -H_{mag}\frac{l_{mag}}{\delta_{air}} \tag{2.2}$$

Furthermore:

$$B_{air} = \frac{\Phi_{air}}{A_{air}} = \frac{\Phi_{mag}}{A_{air}} = \frac{B_{mag}A_{mag}}{A_{air}} \text{ and } H_{air} = \frac{B_{air}}{\mu_0} = \frac{B_{mag}S_{mag}}{\mu_0 S_{air}} \tag{2.3}$$

From the equations (2.1) (2.2) and we get after modification:

$B_{mag} = -N_d H_{mag}$, where

$$N_d = \mu_0\frac{l_{mag}\,S_{air}}{l_{air}\,S_{mag}} = 4\pi\cdot 10^{-7}\frac{0.006\cdot 2\cdot\pi\cdot 0.0075\cdot 0.0015}{0.0055\cdot(\pi\cdot 0.0075^2-\pi\cdot 0.003^2)} = 6{,}528\cdot 10^{-7} \tag{2.4}$$

$$B_{mag} = -6{,}528\cdot 10^{-7}\,H_{mag}$$

According to the permanent magnet manufacturer [8] the remanent magnetic field and a coercitive magnetic field intensity are within a certain range and therefore the average value has been taken and the directional shape of the line was determined. This assumption has been made because the actual B-H characteristic is unknown.

$B_r = 1.32 - 1.37 => 1.305$ T

$H_c = 860 - 995 => -907.5$ kA m^{-1}

B-H characteristics:

$$B_m = 1.438\cdot 10^{-6}H_m + 1.305 \tag{2.5}$$

Results of the intersection of the load line with the B-H characteristics:

$H_{air} = -464594{,}68$ A m^{-1}

$$B_{air} = 0.407 \text{ T} \tag{2.6}$$

This calculation was done for air gap δ_{air}=5.5 mm. If the air gap must be increased because of a mechanical construction of VCA, demagnetizing factor decreases on a value N_{d1} to the working point A1 as can be seen in a Fig. 8.

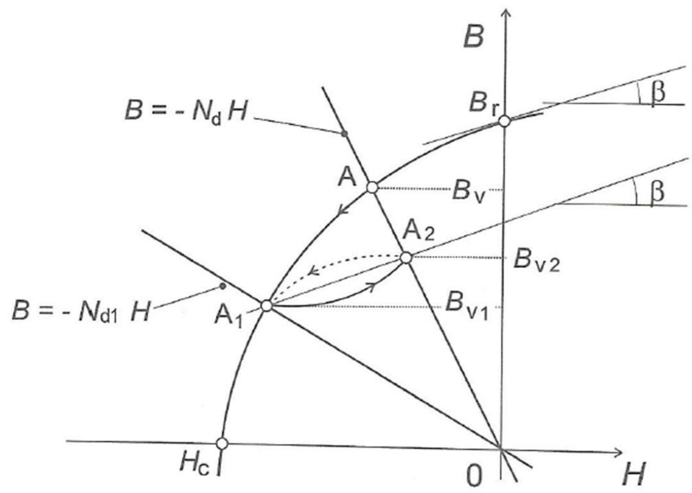


Fig. 8 Process of demagnetizing the magnetic circuit with an air gap [7]

Calculation of B_{air} using equivalent circuit Fig. 7 b)

Rare earth magnets allow an approximation of their B-H – characteristics with linear equation, providing nice relationship for their magnetic resistance [1]:

$$R_{mag} = \frac{V}{\Phi} = \frac{H_c\, l_{Mag}}{B_r S} = \frac{907500 \cdot 0.006}{1.305 \cdot (\pi \cdot 0.0075^2 - \pi \cdot 0.003^2)} = 28108371{,}63\ \mathrm{H}^{-1} \quad (2.7)$$

Next step in the calculation is to calculate the magnetic flux of this circuit:

$$\Phi = \frac{H_c\, l_{Mag}}{R_{mag} + R_{mG} + R_{mFE}} \quad (2.8)$$

Where R_{mG} *and* R_{mFE} are:

$$R_{mFE} = \frac{1}{\mu}\frac{l}{S} = \frac{1}{4\pi \cdot 10^{-7} \cdot 1000} \cdot \frac{0.042}{(2 \cdot \pi \cdot 0.0075 \cdot 0.0015)} = 472832{,}42\ \mathrm{H}^{-1} \quad (2.9)$$

$$R_{mG} = \frac{1}{\mu_0}\frac{\delta_G}{S} = \frac{1}{4\pi \cdot 10^{-7}} \cdot \frac{0.0055}{(2 \cdot \pi \cdot 0.0075 \cdot 0.0015)} = 61918531{,}52\ \mathrm{H}^{-1} \quad (2.10)$$

and flux density

$$B_{air} = \frac{H_c\, l_{Mag}}{(R_{mag} + R_{mG} + R_{mFE})A} = \frac{907500 \cdot 0.006}{(90499735.57) \cdot (\pi \cdot 0.0075^2 - \pi \cdot 0.003^2)} = 0{,}405\ \mathrm{T} \quad (2.11)$$

Value of B_{air} is same using different calculation procedure, however, this calculation cannot be used for a coil design, because of side propagation of magnetic flux on the edges of the air gap, therefore for further calculation only value B_{air} from simulation chap. (2.4.4) will be used.

2.3.2 Lorentz force

Electrodynamic actuators are based on the Lorentz force [1]. This force is defined as:

$$\vec{F} = q(\boldsymbol{E} + \vec{v} \times \vec{\boldsymbol{B}}) \tag{2.12}$$

$\vec{F}$[N] – vector of a force

q [C] – particle of a charge

$\vec{v}$[m/s] - velocity

E – electrical field

$\vec{B}$ [T] – vector of magnetic flux density

From the Lorentz force equation, the force on an N-turn coil of average turn length l is [11]:

$$F_{lorentz} = B_{air}IlN \tag{2.13}$$

Where B is the magnetic flux density perpendicular to the coil direction and F is perpendicular to both B and the coil direction according to the right - hand rule [11]. That can be seen in the Fig.9.

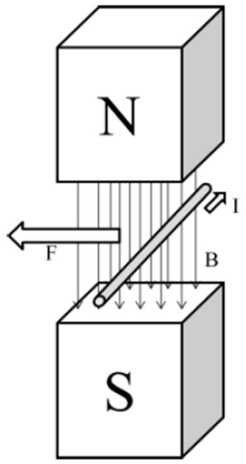


Fig. 9 Effect of a Lorentz force in a magnetic field [1]

In order to maximize generated output force $F_{Lorentz}$ there will be an effort to optimize each component of (2.13) equation. In my case, there is limited space available. That means that number of windings and average coil turn are limited.

Calculation of Lorentz force of VCA

We put now the known variables into the (2.13) equation and we get:

$F = B_{air}IlN = 0{,}20 \cdot 4{,}07 \cdot 0{,}06602 \cdot 170 = 9.21$ N

However, the simulation shows a slightly different result, because B_{air} is not uniform in the area of the whole coil. Lorentz force calculated by the finite element simulation Chap. 2.3.4 is more exact and therefore will be used for further design.

2.3.3 Coil design

Magnetic actuators and sensors are often components of large systems. Such an actuator must be reliable in the system´s environment.

First of all, it is needed to know what maximal current, can flow in the coil, that can be determined from Ohm's law. We will get a maximum current, which can be used.

The resistivity of a coil is:

$$R = \frac{l}{\sigma\, S_c} \tag{2.14}$$

, l is length of the conducting coil wire, σ is its conductivity, and S_c is a cross-sectional area of the wire. The conductivity is a temperature dependent and can be calculated for a copper as:

$$\sigma = \frac{5.8 \cdot 10^7}{1 + 0.00393(T - 20°\mathrm{C})} = 58000000\ , \tag{2.15}$$

where T is temperature at room temperature - 20 °C

$$F_p = \frac{N S_c}{S_w}\ , \tag{2.16}$$

where S_c is a copper cross-section and S_w is a cross-section of whole winding of the coil.

$$S_c = \frac{\pi \cdot d^2}{4} \tag{2.17}$$

One does not choose any wire diameter *d*, but an available wire gauge. The American Wire Gauge (AWG) is quite commonly used and it is a number, that gives the bare-wire diameter. [4]

Packing factor F_p is typically only about 75% even when the wires are tightly wound. Conservative designs assume a maximum P=0.7 or less. [11]

For an equation (2.21) we will calculate l_T – a length of one turn of a coil. We will calculate coil for NI=650. This number is based on simulation, where we need to have a Lorenz force greater than 5.5 N. Lorenz force must be able to overcome weight of all moving component and also force of springs, which are working again this force. In the haptic demonstrator, different spring will be used, in order to determinate the best damping effect of the moving part of the actuator. $F_{Lorentz}$ is chosen, a little bit higher, than actually needed, so that there is a room for testing different springs.

$$F_{Lorenz} > F_{spring} + F_a \quad (2.18)$$

Formula for calculation resistivity of a coil is [4]:

$$R = 4\frac{Nl_T}{\sigma\pi d^2} \quad (2.19)$$

The other key equation is based on Ohm´s law [4].

$$NI = \frac{NU}{R} \quad (2.20)$$

Substituting (2.16) and solving for the bare diameter results in [4]:

$$d = \sqrt{\frac{4NIl_T}{\sigma F_p \pi U}} = \sqrt{\frac{4\cdot 650\cdot 0.06597}{5.8\cdot 10^7\cdot 0.7\cdot \pi\cdot 12}} = 3.35\cdot 10^{-4}\ \mathrm{m} \quad (2.21)$$

The available diameter, which can be bought is 0.35 mm. With known diameter a number of turns of a coil can be calculated:

$$N = \frac{F_p S_w}{S_c} = \frac{0.7\cdot 0.0035\cdot 0.006}{\pi\cdot 0.000175^2} = 153 \quad (2.22)$$

Start lead and end lead of the coil must be on the same side, so one needs an even number of winding layers as can be seen on Fig. 10. According to this figure, the coil was wound.

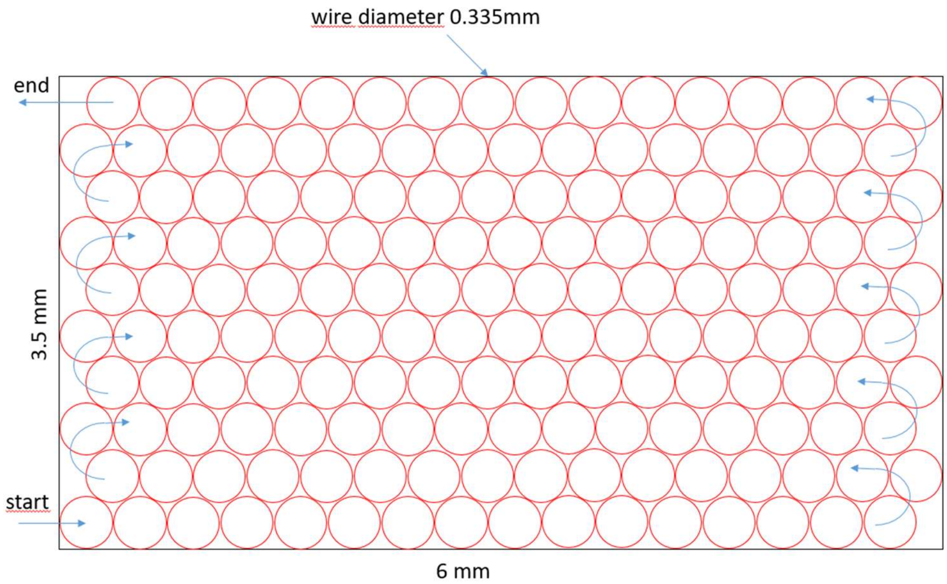


Fig. 10 Winding space of a coil

Thus each turn of a coil carries I= 650/167=4,07 A. Actuator should vibrate only for very short time approx. 0.1ms second, thus current will flow only 0.1ms.

Joule–Lenz law

According to [4] Joule heating, also known as Ohmic heating and resistive heating, is the process by which the passage of an electric current through a conductor produces heat. This heat is generated by the collisions of the moving electrons with the other metal particles in which the electric current spreads. Larger current cause more frequent particle collisions, thus releasing much of the heat. This heat is described by Eq. (2.23).

$$Q = UIt \text{ [J]} \tag{2.23}$$

Q [J] heat generated

U [V] voltage on the end of conductors

I [A] current passing through the circuit

t [s] the length of time the electrical current passes through the conductor

The described relationship of Joule-Lenz's law can be modified by Ohm's law and relationship describing the dependence of the electrical resistance of the conductor on its length and cross-section. The resulting relationship looks as follows:

$$Q = \left(\rho \frac{l}{S}\right) I^2 t \text{ [J]} \tag{2.24}$$

Q[J] heat generated

ρ [$\Omega mm^2 m^{-1}$] specific electrical resistance of the conductor material

l [m] length of a conductor

S [mm^2] conductor cross section

I [A] current flowing

t [s] the length of time the current passes through the conductor

Formation of a heat should be usually taken into account when VCA is designed. This heat can cause unwanted warming of the moving coil. Due to excessive heat, the insulation of the conductors can be broken and the locomotive windings will be destroyed. One can choose wire for a coil which insulation can withstand higher temperatures. However, there is not needed to be known how much will the coil heat up, because it runs for a very short time and the wire is well dimensioned for such currents. Maximum vibration time will be 20ms, then there will not be any vibration possible for 20ms. This cool down phase will be done by software.

A thermal simulation was not the subject of this work, however, when needed it would be possible to do it with some 3D CAD program such as Solid Works. One could calculate heat using equation (2.24) and then choose thermal analysis and used materials.

2.3.4 Simulation of VCA´s magnetic field using finite element method

To get a more precise results of a calculation a simulation of a magnetic field was performed. This simulation was done in a program called Agros2d. Magnetic circuit calculation using the finite element method. According to [9] this is a method for the numerical solution of boundary value tasks. For example, the solution of differential equations under given boundary conditions. Since many problems can already be solved with a two-dimensional (2D) calculation, due to the simplicity of the FEM below, only the calculation of plane and rotationally symmetric magnetic fields is considered. A prerequisite for the application of this method is the knowledge of an equation describing the field problem. For the electromagnetic fields, Maxwell's equations form the basis of the calculation. For stationary magnetic fields applies [9]:

$$rot\ H = J \tag{2.25}$$

$$div\ B = 0 \tag{2.26}$$

To solve the field equation, it is advantageous to introduce the magnetic vector potential A. For this vector potential [9]:

$$B = rot\ A,\ div\ A = 0 \tag{2.27}$$

Using equation (2.12), an equation describing the field is obtained [9]:

$$rot\ \frac{1}{\mu} rot\vec{A} = J_{ext} = 0 \tag{2.28}$$

From the equation (2.15) we get after modification [9]:

$$rot \frac{1}{\mu}\left(rot\vec{A} - \overrightarrow{B_r}\right) = 0 \tag{2.29}$$

The boundary value of A=0 was set into the simulation on the edges of the half circle as shown in Fig.11.

For the simulation is needed to know the relative permeability of a magnet, which can be calculated using a form for relative permeability and datasheet of a used magnet [8], average value has been taken.

$$\mu_r = \frac{B_r}{H_c \mu_0} = 1.144 \tag{2.30}$$

Current density in a coil is equal to:

$$J = \frac{NI}{S} \cdot F_p = \frac{167 \cdot 4.03}{(3.5 \cdot 6)} \cdot 0.7 = 21.66\ [\mathrm{A \cdot mm^{-2}}] \tag{2.31}$$

When we put these data into the program we will get a simulation, where a density of magnetic flux in an air gap is $B_{air} \approx 0.20$ T with an air gap of $\delta_{air} = 5.5$ mm. Between coil and iron is a coil holder, which is made of aluminum. On the left side next to the magnet is a space for a center pin of a magnet, which is also made from aluminum. Aluminum has relative permeability also close to one, therefore it is also not necessary to be simulated.

One can influence the Lorentz force with iron used. That means higher permeability of iron, greater force action on the coil, but in case of this actuator only in range of 0.1-0.2 N. Originally a smaller magnet with no hole in the middle was intended to be used, but because of a center pin this magnet was used. The final simulation can be seen on a Fig. 11. This simulation was done based on the mechanical requirements so that the coil can be fastened into the coil holder. The coil is place as close as possible in the air gap, in order to increase the efficiency of the actuator. A smaller air gap results in greater Lorentz force.

This simulation was performed 2D because this actuator is a rotary symmetric. From the simulation, one can see a significant drop in the density of magnetic flux in the air gap compared to a magnetic flux density in a magnet. Magnetic flux flows over the air gap and closes over a steel into the permanent magnet. There is also not insignificant propagation of magnetic flux over a lid of a magnet which is made of steel, which only confirms, that calculation of magnetic flux in the air gap is correct. Lorenz force is approximately F=5.5N.

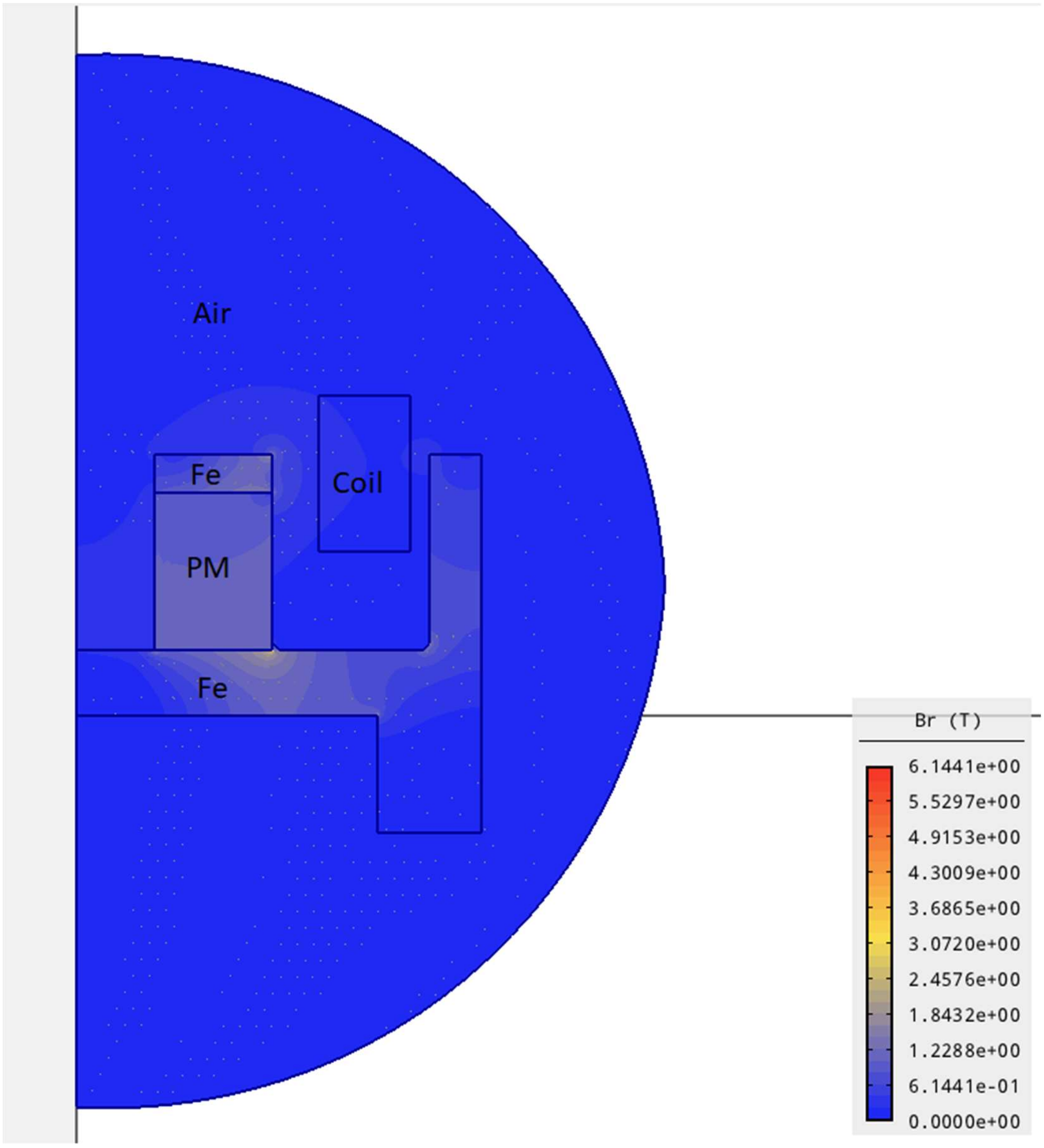


Fig. 11. Simulation of density of magnetic flux of VCA using finite element method

2.4 Concept of a mechanical design of the actuator

Mechanical design of the actuator was based on the simulation of a density of magnetic flux. Mechanical design was done in cooperation with a mechanical department of Continental Engineering Services.

VCA consist of one movable and one stationary part. The movable part is the coil assembly, stationary part is the magnet assembly, spring and bottom plate. The whole concept can be seen in a Fig. 12.

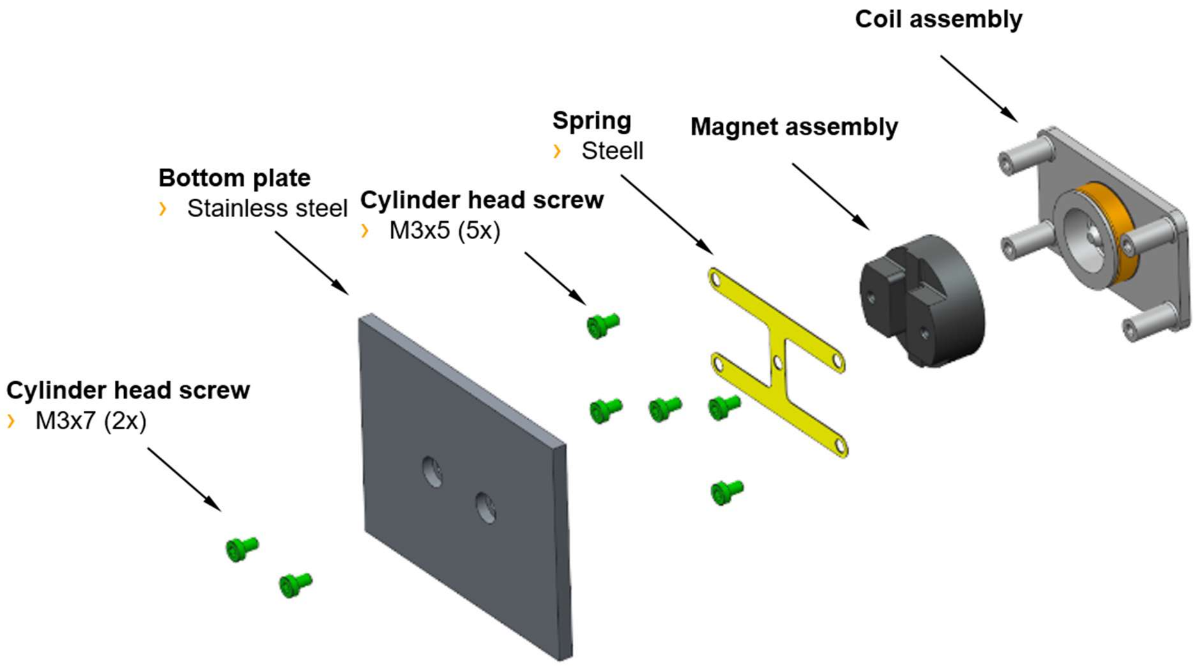


Fig. 12 Concept overview [13]

All the components besides magnet assembly and spring cannot be ferromagnetic, because magnetic flux would close differently as simulated. A bottom plate is made of stainless steel. Springs with different thickness can be used in order to determinate best damping effect of the spring. Spring also has a function to hold together the moving and the stationary part of the actuator with 5 screws as it is shown in a Fig. 12.

In Fig. 13 is shown an assembly of the coil. A coil holder and a coil bobbin are divided in order to wind the coil easily. It is essential that the sunk screw is not ferromagnetic, because then would a magnetic flux would not close over an air gap, but partially over the screw. Aluminum was used for the coil holder and rest not ferromagnetic parts because it can be easily manufactured and it allowed to have a very close gap between the parts.

Another option was to print the supporting parts on the 3D printer. Originally a special wire was intended to be used to make a coil, which can be baked on a certain temperature, however, such a coil holder cannot withstand higher temperatures. This wire has a better efficiency as a laminated copper wire. The wire would be a good option also for an aluminum holder, but such a special wire was not available to buy.

As it has been already mentioned the actuator is designed on a maximum force of a 5.5 N. Aluminum is a good choice for a coil holder, because it can be easily assembled together. For the next model of the actuator, a coil holder made from plastic would be a better choice because of its lightweight. It would allow the voice coil actuator to carry more weight.

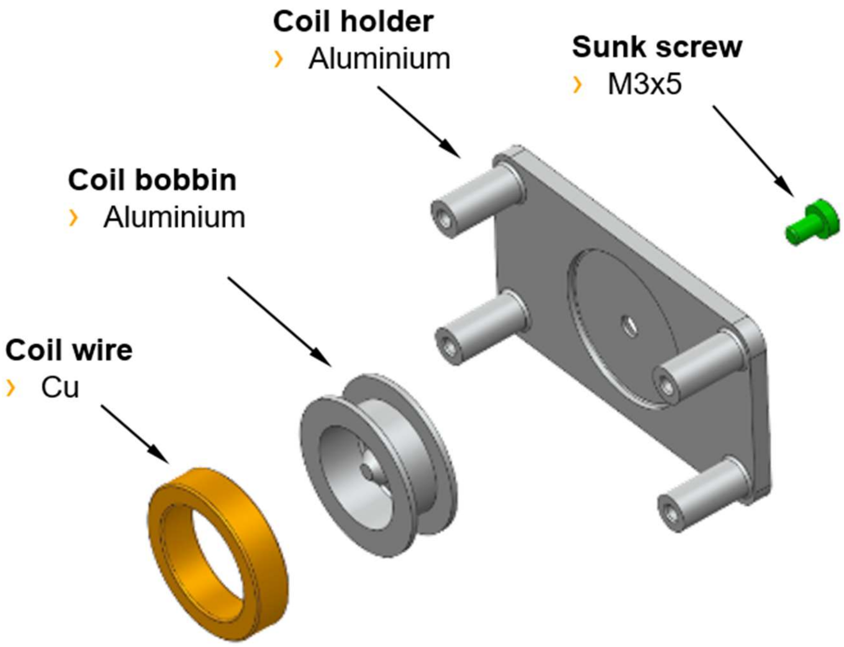


Fig. 13 Coil assembly [13]

Magnet assembly consists of a metal plate, a magnet pot, and a neodymium magnet. First two parts must be ferromagnetic. Reason to have the metal plate is to transfer magnetic flux over the air gap. This neodymium magnet [8] has been chosen, because of its great magnetic properties and it also has the hole inside, which is important to center the whole magnet assembly. This assembly is shown in the Fig. 14. The magnet will be glued together with a metal plate and magnet pot.

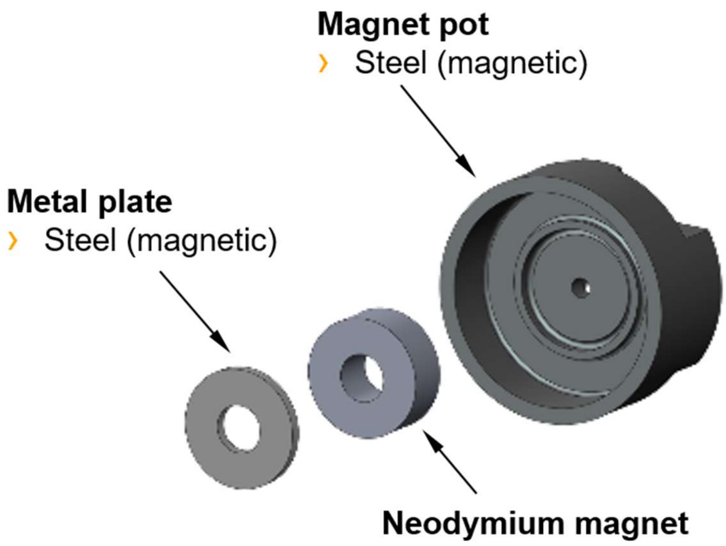


Fig. 14. Magnet assembly [13]

2.4.1 Manufactured and assembled actuator

Parts of actuators were manufactured and two actuators were assembled, each of these actuators has a different spring. One spring is 0.3mm thick and second is 0.5mm thick. This actuator can be seen in a Fig. 15. A coil holder with a coil bobbin and coil are the moving parts. Coil was wound according to the Fig. 10. The coil was wound as well as possible. It was the most demanding manual part of my thesis. Every layer of a wire was marked on a few places with a permanent highlighter in order to know, that the wire is wound over the last layer properly. A fingernail and tweezer were used to adjust winding so that they are as tight as possible.

The button of the actuator can be pressed about 1-2mm, according to how strong one pressed the button. The bottom plate has also holes for screws in order to fasten PCB. In the middle is a supporting protrusion to support a PCB from a bottom side, however, due to a misunderstanding with a mechanical department of company CES it cannot be used because in a layout is populated a THT processor and a short circuit could occur. I solve this problem using a washer under a PCB so that the PCB will be higher and pins cannot be connected with each other. This change has no effect on a proper working of this device.

Fig.15 Assembled actuator and bottom plate for fastening of the PCB

In a Fig.16 can be seen VCA actuator from the side. The damping material can be seen glued to a bottom of a magnet pot. A damping material is used in order to avoid unwanted noises during the vibration. In Attachment A can be found a list of used material for this actuator and in Attachment B are dimensions of the actuator. The actuator can be pressed and it moves 1-2mm depending on a force and spring used.

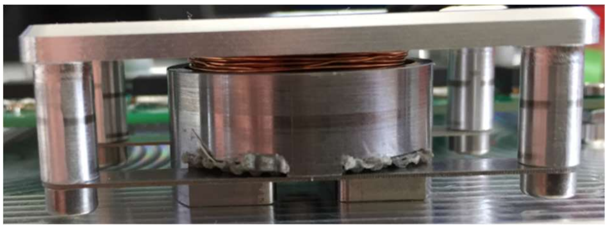


Fig. 16 Actuator side view

2.5 Equivalent circuit of VCA and simulation of induced voltage

According to the [12] an electrical equivalent circuit can be used as shown in Fig. 17.

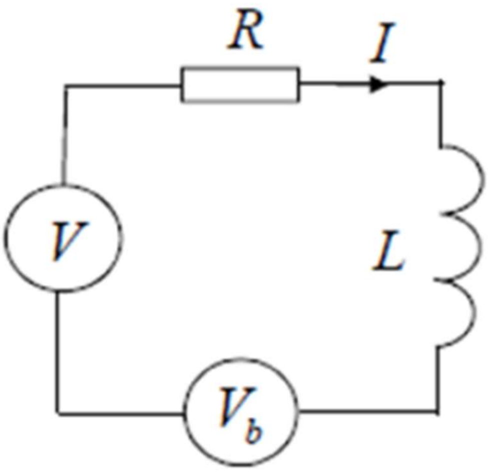


Fig. 17. Equivalent circuit of VCA [12]

V [V] acting voltage

R [Ω] resistance of a coil

L [H] coil inductance

V_b[V] induced voltage

For the simulation of a VCA, I must estimate inductance and induced voltage. Conductor, where electric current is present is becoming a source of a magnetic field – it generates magnetic flux around itself [7].

$$\Phi = LI(t) \text{ [Wb]} \tag{2.32}$$

The magnetic flux is directly proportional to the flowing current. With a time change of the current flowing, a voltage will be induced according to the Faraday´s law [7].

$$U_{ind} = -\frac{d\Phi}{dt} = -\frac{d}{dt}(LI) \text{ [V]} \quad (2.33)$$

$$U_{ind} = -L\frac{dI}{dt} \text{ [V]} \quad (2.34)$$

It is clear from the equations that the induced voltage is inversely oriented to the change of electric current that has occurred [7].

In order to do a signal analysis of the sensing circuitry, it must be roughly estimated how much voltage can be induced in a coil when the button is pressed. For magnetic flux perpendicular to the coil windings, induced voltage can be defined [7]. We will assume that the speed varies in time and distance linearly and we will replace it with a linear distance traveled over a time and we will get:

$$U_{ind} = B_{air} \cdot l_w \cdot v = B_{air} \cdot l_w \cdot \frac{s}{t} = 0.2 \cdot 0.066 \cdot \frac{0.001}{0.1} = 0.132 \text{ mV} \quad (2.35)$$

v – velocity of the finger

l_w – average length of a coil winding

B_{air} – density of magnetic flux in the air gap

Induced voltage was calculated for a various velocity of a button push and it is typified it in Fig. 18. It uses as a parameter Eq. 2.35. In this equation, a velocity was changed in dependence on, how quickly the button is pressed. The problem with this method is that it is not known exactly, what is the velocity of finger acting onto a button, therefore only reasonable ranges of velocity were taken. Velocity also represents time and distance of a pressed button as is shown in Eq. (2.35).

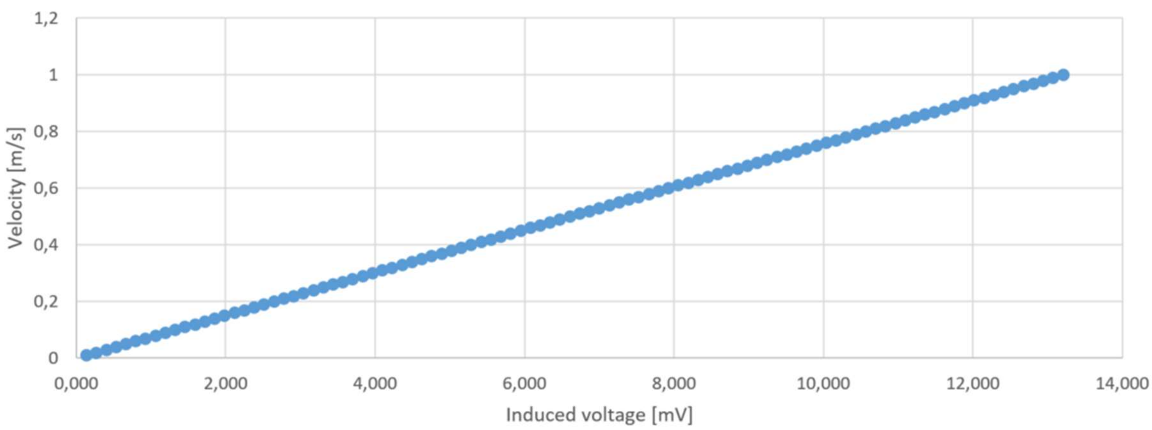


Fig. 18 The relationship between push button speed and induced voltage

For a coil of NI ampere-turns, each of the turns is coupled with a magnetic flux Φ, we will introduce magnetic flux of a coil $\Phi_c = N\Phi$ and we get [7]:

$$L_d = \left|\frac{d\Phi_c}{dI} = \frac{dNBS}{dI}\right| \; [H] \tag{2.36}$$

If a coil is a non-linear (in its surroundings is ferromagnetic) and its weber-ampere characteristics is a curve [7]. However, inductance must be not calculated, because it can be measured. Equation (2.36) is here mentioned because it is important to know that this coil has a dynamic inductance. The inductance of a coil was measured. This coil was already assembled together with a permanent magnet and metal plate. These two parts are also core of the coil. An inductance of a measured coil, when a button is not pressed is L=0.1 mH. This value will be later used in the simulation.

2.6 Force feedback - Inductive measurement (Magnetic sensors)

This measurement will take care of a part called force sensing. Measurement how much is the VCA moved is essential to know in order to properly drive this actuator to get a certain vibration.

Electromagnetic and electrodynamic actuators already need a magnetic field to generate forces. According to [1] magnetic sensors can be further divided. Sensors for static fields, field planes, hall- sensors, and a sensor for induced currents and time-dependent fields can be distinguished.

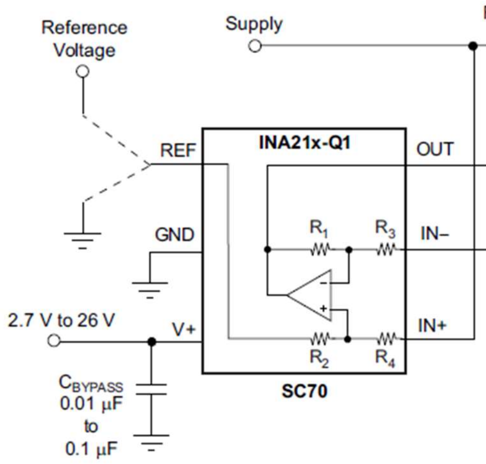
2.6.1 System of an inductance sensor

In this case, changing the inductance of the system is measured in order to detect a position of moving parts in the Voice coil actuator. Many parameters like the magnetic permeability of a material in a coil influence an inductance of a system. According to [1] using a measurement of inductance of a coil can be made if a ferromagnetic material moves in between the coil as a position-depending core. A simple electronic for measuring inductance is the use of an LR- serial circuit, which for example with a microcontroller – is triggered by a voltage step. The measurement value is given by the time the voltage at the resistor needs to trigger a comparator voltage. The duration encodes the inductance, assuming a constant resistance. For the actual design, it has to be considered, that the wounded coil has an own resistance, which cannot be neglected. As an alternative a frequency nearby the resonance L/R of the LR- circuit can be applied. The voltage amplitude measurement varies in dependence on the inductance´s detuned by the movement of the ferromagnetic core.

2.6.2 Simulation of a current sensing circuitry

It is clear that the quicker the button is pressed, the greater will be the induced voltage. An equivalent circuit of VCA - Fig. 17 is used in the simulation of sensing circuitry.

The essential part of a sensing circuitry is a component called INA212-Q1, which is basically a current-shunt monitor, also called a current-sense amplifier. Simplified schematics of this differential amplifier is in Fig. 19 [14].



PRODUCT	GAIN	R_3 and R_4	R_1 and R_2
INA210-Q1	200	5 kΩ	1 MΩ
INA211-Q1	500	2 kΩ	1 MΩ
INA212-Q1	1000	1 kΩ	1 MΩ
INA213-Q1	50	20 kΩ	1 MΩ
INA214-Q1	100	10 kΩ	1 MΩ
INA215-Q1	75	13.3 kΩ	1 MΩ

$V_{OUT} = (I_{LOAD} \times R_{SHUNT})\ Gain + V_{REF}$

Fig. 19 Simplified schematic of a component INA212-Q1 [14]

From a table can be seen that gain of this component is 1000. This simplified schematic in Fig. 19 was used for the simulation because for an older version of PSpice model of a component could not be used.

In a Fig. 20 the simulation setup of the current sensing circuitry is shown. This simulation was done in a program called PSPICE. What is needed from the simulation is, to approximately determine the voltage on an ADC pin of a processor. In the simulation, there is a voltage marker. The voltage marker in Fig. 20 is the place, where is the AD converter.

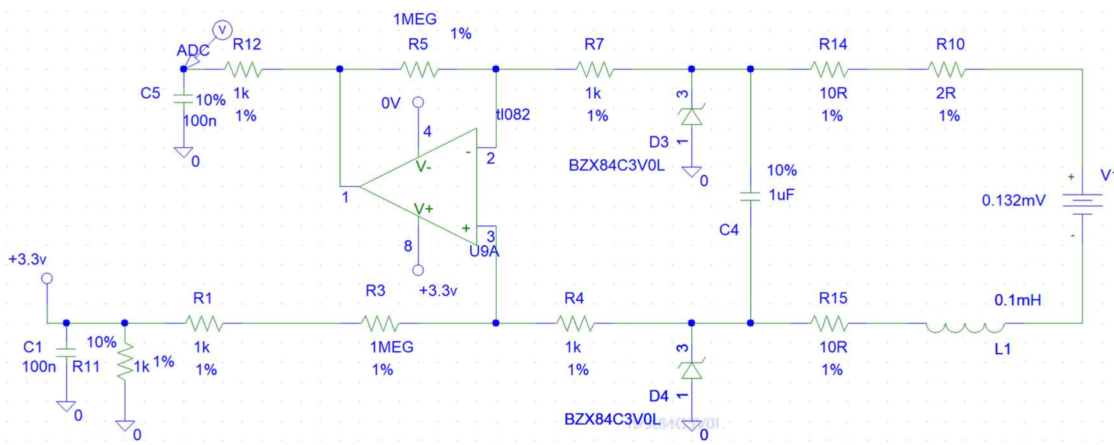


Fig.20 Simulation of an induced voltage measuring circuitry

Basically, the reason for this simulation is, that it is needed to determinate if the component can be used in a layout. Purpose of this circuitry is to sense induced voltage as little as 0.1 mV, then amplify this voltage. The voltage must be amplified so that it can be safely read in an analog-digital converter in a processor. The voltage on an ADC pin can be maximally 3.3V. This processor will have 10 bits AD converter. Atmega16 has a resolution of 10 bits so it has 1024 quantization levels. The resolution of the converter indicates the number of discrete values it can produce the range of analog values. The resolution defines the magnitude of the quantization error and it can be also defined electrically and expressed in volts. The minimum change in voltage required to guarantee a change in the output code level is called the least significant bit (LSB) voltage. The resolution Q of the ADC is equal to the LSB voltage. The voltage resolution of an ADC is equal to its overall voltage measurement range divided by the number of intervals [15]:

$$Q = \frac{E_{FSR}}{2^M} = \frac{3.3}{2^{10}} = 3.22\ mV, \tag{2.37}$$

where M is the ADC's resolution in bits and E_{FSR} is the full scale voltage range.

2.6.3 Worst case analysis of a sensing circuitry

This analysis was done also in a PSPICE program. Worst case analysis was done only for a critical part of a circuit, which is in this case a measuring circuitry. This analysis includes all components of a sensing circuitry. Simulation on Fig. 20 has been used. In a Fig. 21 can be seen, how can tolerance of a components change a voltage on a pin of a processor, which is an input of the analog-digital converter. This voltage is in a range from 718mV up to 850mV for an induced voltage of 0.132mV.

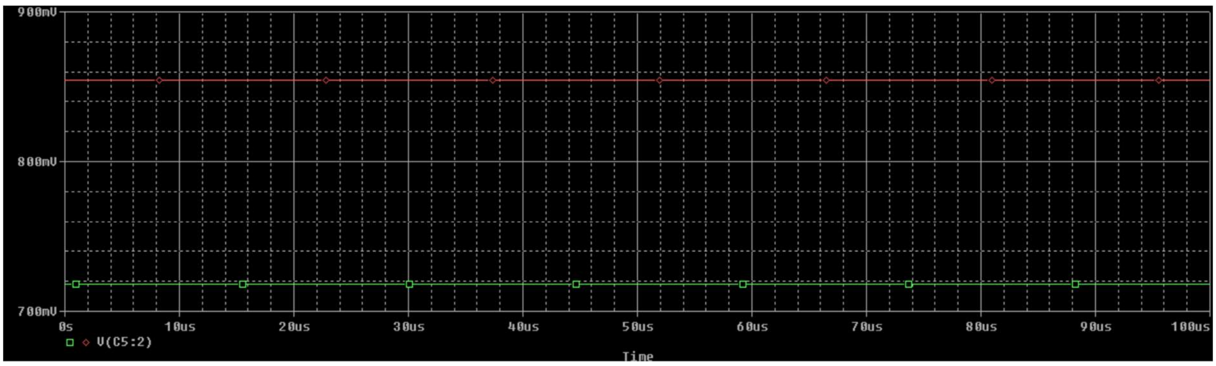


Fig. 21 Worst case analysis of a sensing circuitry

2.7 Simulation of a driving circuitry

The purpose of this simulation is to realize how does H-bridge works and in order to determinate which component should be used. Unfortunately, any PSPICE model for the component which I wanted to use wasn´t found. A solution was to replace n- and p-MOSFETs available in the simulation program. As a p-Channel MOSFET a component irf9520 was used, for n-Channel irf740 was used.

In the Fig. 22 is shown schematic for simulation of the half of a H-bridge. Firstly, one half of a H-bridge was simulated, therefore the other two MOSFETs in a circuit are shut down. The result of this simulation can be seen in a Fig. 23.

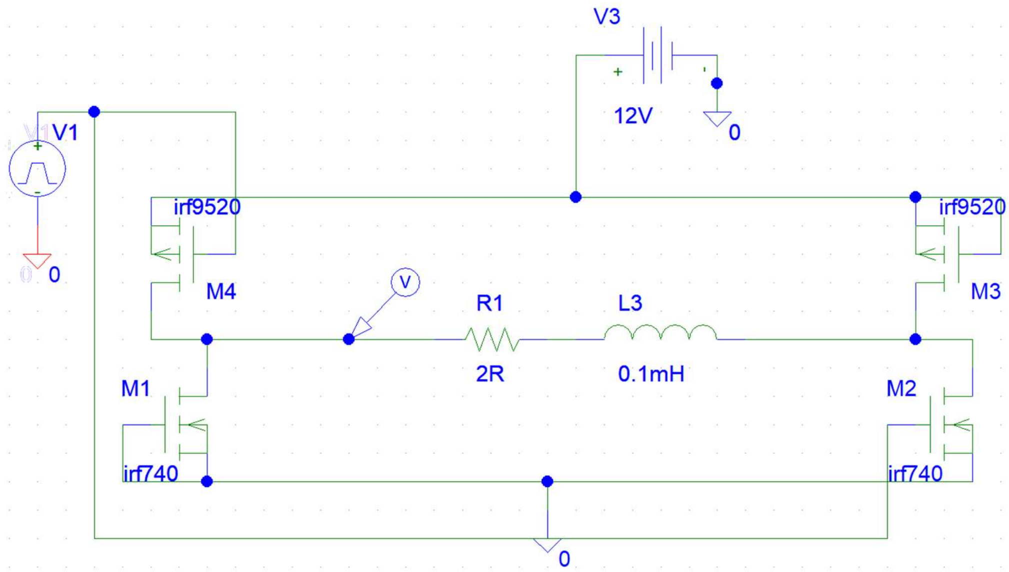


Fig. 22 Simulation of a half driving circuitry

When driving signal in a Fig. 22 is changed so that it drives other two MOSFETs –M1 and M3. The other two MOSFETs –M4 and M2 are shut down. The MOSFETs M1 and M3 are driven with a reverse pulse as it can be seen in Fig.24. An oscillation in those two figures is present. This oscillation is caused by an inductance, when the simulation without the inductance was performed, a nice rectangular signal was seen.

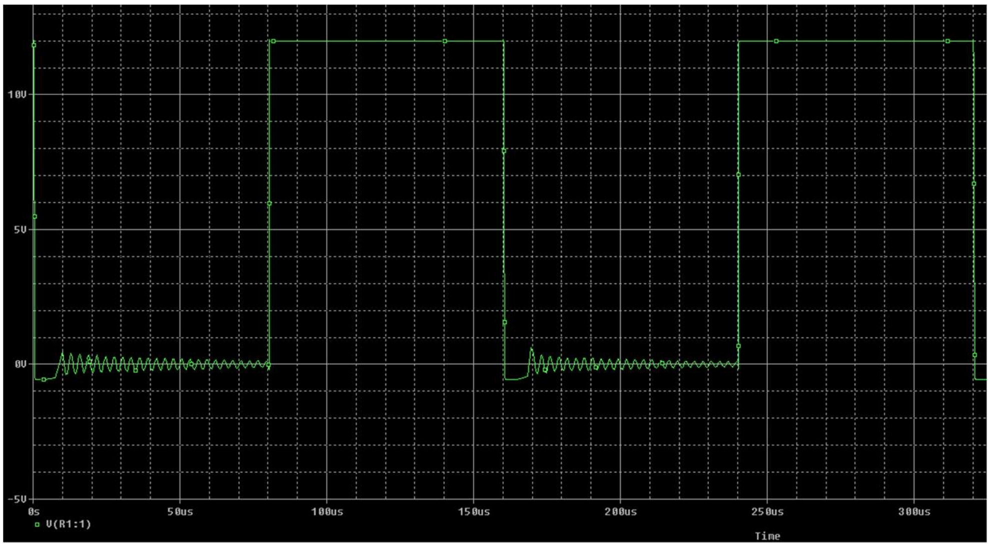


Fig. 23 Driving signal of a first half of a H-bridge in the actuator

From the Fig. 23 and Fig.24 is nicely seen, that with H-bridge with exactly this driving signals a short circuit would occurred. Therefore, a component with a driver IC with self-generating dead time was used.

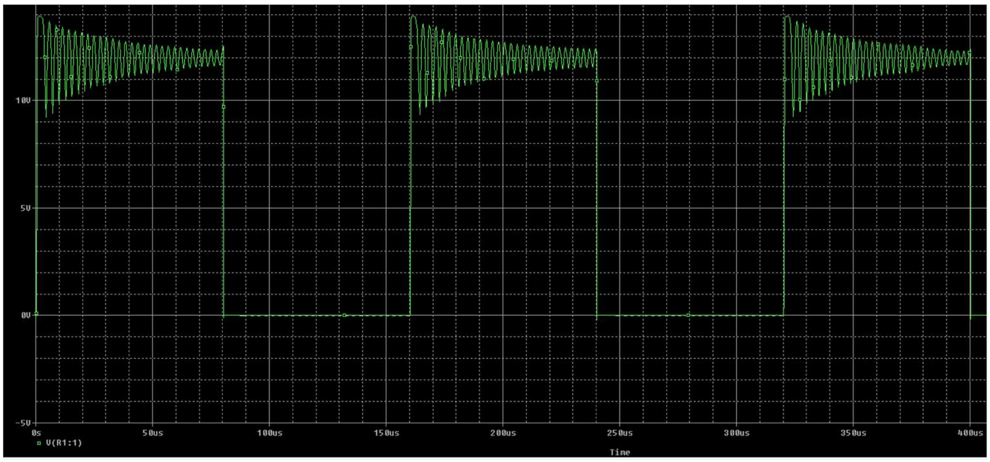


Fig. 24 Driving signal of a second half of a H-bridge in the actuator

3 PCB design

After the simulation of a sensing and driving circuitry a schematic of a PCB for a haptic demonstrator can be made.

Design of this PCB was done in a program Altium Designer 18. PCB for my master thesis should include driving and measuring circuitry. A simplified circuit is shown in a Fig. 23. It contains a processor, a H-bridge and a measuring circuitry. Both, the H-bridge and the sensing circuitry are connected with the actuator. In order to determine what processor will be used is needed to know, how many ADC, GPIO, PWM pins is present to a disposal. It was found that 8 pins for ADC, 4 GPIO, 4 PWM pins are needed. For a driving of a single H-bridge 2 GPIO, 2 PWM and 1 ADC pins are needed.

A simplified circuitry is shown in Fig.23. is in the PCB 2 times because the PCB is made to control 2 actuators at the same time to make it the design more modular. Later, not in this thesis, can be built a haptic demonstrator with two actuators. However, in this thesis, only one actuator is used.

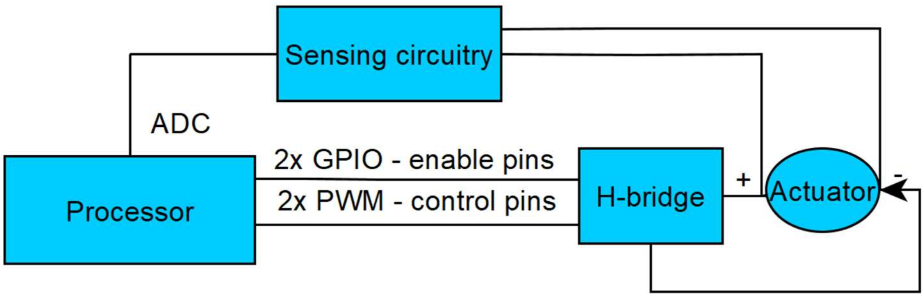


Fig. 23 Simplified schematics

3.1 Schematics and used components

In this chapter is described a schematic of the PCB and also the most important components will be mentioned. The whole schematic can be found in an Attachment C. In Attachment D the PCB BOM (bill of material) is included.

Because this device is supposed to be for an automotive use it is developed in order be fully functional in the voltage range of 9-16V. In Fig. 24 is shown the main connector and polarity protection for a processor and components, which are using voltage 3.3V. After connector, there is bypassing and decoupling capacitor. Polarity protection is done by Schottky diode. One mistake in a schematic occurred, Schottky on a net VCC should be added as well, because of the polarity protection and this has been forgotten, because a separate net VCCP on the end of PCB design was added, so that power supply for microcontroller and actuator are separated.

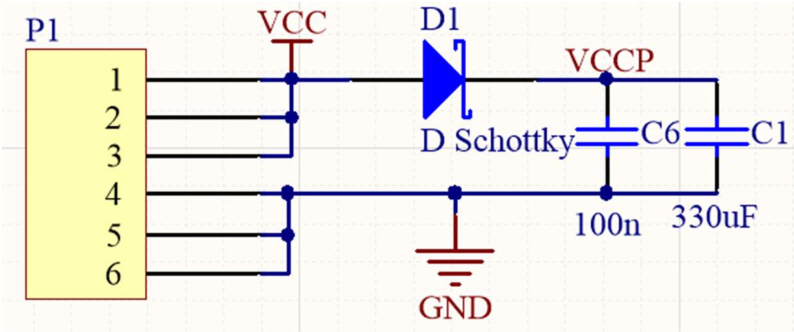


Fig. 24 Connector and polarity protection

Power blocking

The need to use blocking capacitors is based on the fact that the signal delay is not zero and therefore any other power supply is already too far from its appliance. Blocking capacitors are divided into filter, local and bulk. The filter capacitor (most commonly electrolytic) serves as a broadband filter, eliminating the influence of the inductance of the supply from the power supply and the contact transient resistances of the connectors. This capacitor has a higher capacitance but a lower radiofrequency. To improve the high-frequency properties, ceramic capacitors are used, which are given with electrolysis in parallel. The ceramic capacitor is used as a local capacitor. It serves as a local power source for components and reduces pulse currents. These local capacitors should be as close as possible to a consumer such as a microcontroller. When choosing suitable blocking capacitors, one need to monitor their own resonance and use capacitors whose own resonance is higher than the highest frequency in the PCB. [15]

In order to supply processor and other components, whose require a lower voltage than a supply voltage there is a component TS1117B, which generates 3.3V output voltage. This regulator is a low drop regulator. This component can provide current up to 1A.

3.1.1 Processor

The ATmega16 is a low-power CMOS 8-bit microcontroller based on the AVR enhanced RISC architecture [16].

In this PCB an Atmega16-PU is used as a processor because it has enough needed outputs and it can be easily programmed and is automotive specified and can be programmed over an ISP connector. It has 10bit analog-digital converter, such resolution of ADC is enough for this application.

A THT version of this processor is used, because when this component will be placed in a socket so that it can be replaced easily and could be a great advantage when the processor would be accidentally destroyed.

For this processor, an external crystal 16 MHz is used and two capacitors with capacity 15 pF are placed as it is recommended in a [14] data sheet. Two blocking capacitors are connected as close as possible to the power pin of the processor. An external reference voltage of an ADC has been used. AVCC is connected to +3.3V over a low pass filter as it can be seen in a Fig. 25. Pins MISO, MOSI, SCK and RESET are connected to the ISP connector so that the processor can be programmed. To the ISP connector is also connected voltage 3.3V, in order to program processor without a connection of a power supply.

It hasn´t been thought truth, that this processor has no D/A converter, therefore for driving of the actuator with amplitude modulation cannot be used, however in a [1] is written, that PWM modulation is used in most cases for driving of the electrodynamic actuators.

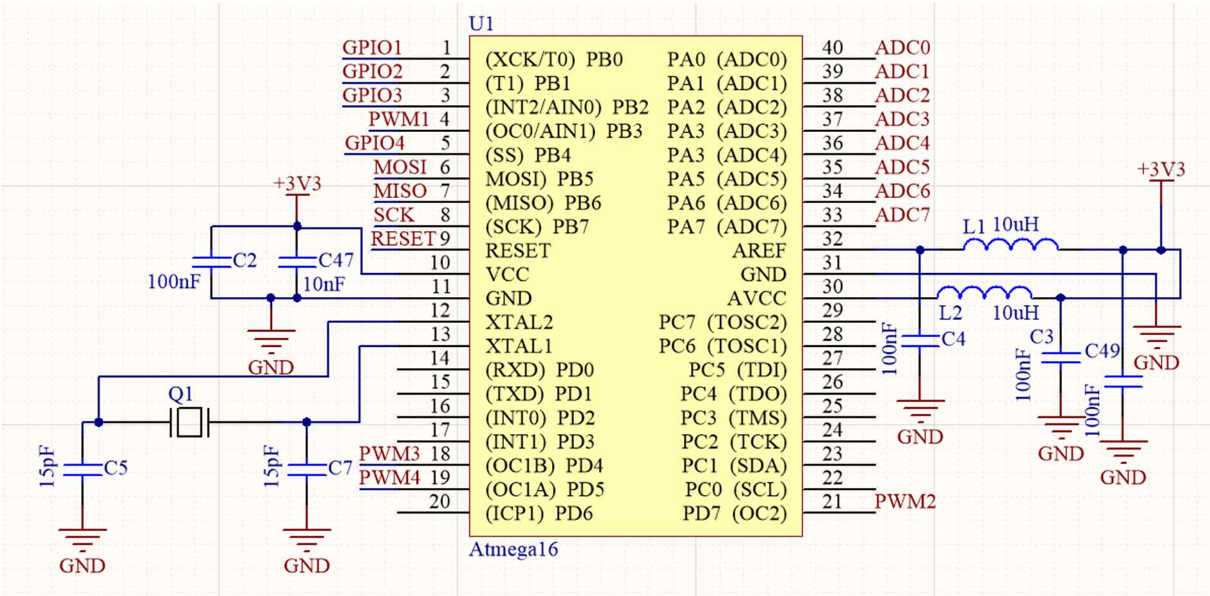


Fig. 25 Schematic of Atmega16-PU

3.1.2 H-Bridge

According to a source [1] the actuator need an analog voltage or current to generate forces and some transformer between the digital signal and analog value is needed. For driving of the H-Bridge a PWM and also a D/A converter can be used. For driving of this actuator the PWM modulation is used.

A H-bridge is an electronic circuit that enables a voltage to be applied across a load in opposite direction. These circuits can be used for an actuator to allow DC motors to run forward or backward. [17]

A H-bridge is a simple circuit, which contains four switching elements. A load is in the center and forms H-like configuration. The switches (Q1-Q4) are usually bi-polar or FET transistors. In the Fig. 26 is shown a H-bridge. The top-end of the bridge is connected to a power supply and the bottom-end is grounded [18].

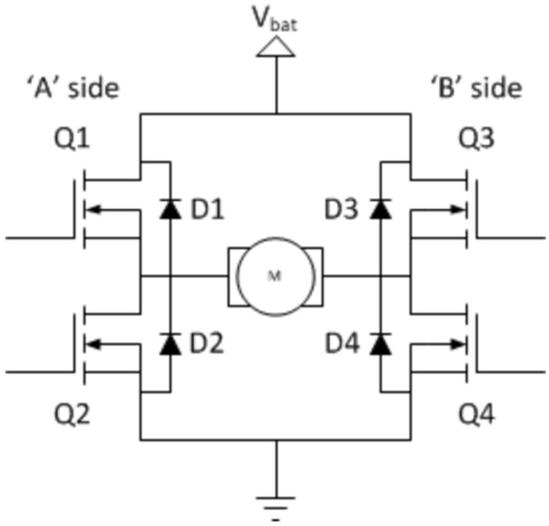


Fig. 26 H-Bridge [18]

H-bridge can operate quite simple. If switches Q1 and Q4 are turned on, the left end of the actuator is connected to the power supply, the other lead is connected to the ground, therefore current flows. In case of a linear actuator, the actuator moves in one direction. When Q2 and Q3 are switched actuator moves in opposite direction. One must avoid switching Q1 and Q2 at the same time, because a really low-resistance path between power and GND was created, effectively short-circuiting your power supply [18].

To form a H-bridge two components called BTN8982TA are used. This component is an integrated high current half bridge for motor drive applications. It contains one p-channel high side MOSFET and one n-channel low side MOSFET with an integrated driver IC in one package. Connection with a microcontroller is done by the integrated driver IC, which has logic level inputs, diagnosis with current sense, slew rate adjustment, dead time generation and protection against over temperature, under voltage, overcurrent, and short circuit. This component has been chosen, because it provides a cost-optimized solution for protected high current PWM motor drives with very low board space consumption. [19]

So-called dead time is generated in a driver IC of this component, because of shortcut, which would occur, when Q1 and Q2 in a Fig. 25 was connected. It is essential to take care of the dead time generation. Board space and automatic dead time generation was a reason, why this component has been chosen. When the component would not had the driver IC with its dead time generation, there was a number of ways, how to generate a dead time. MCU which supports a dead time generation for a PWM would be a solution.

A typical application circuit of this component taken from [19], in order to form a H-Bridge. In the Fig. 27 is shown the H-bridge schematic.

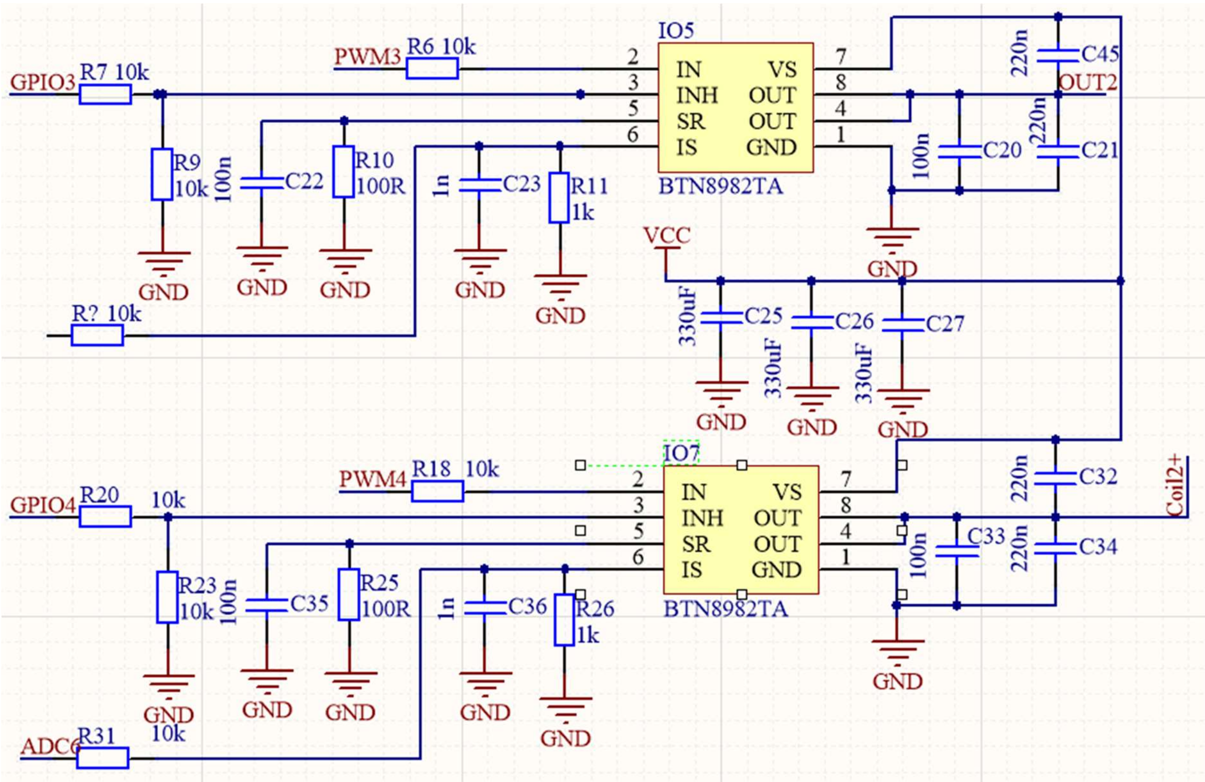


Fig. 27 H-Bridge with two BTN8982TA

The digital inputs need to be protected from excess currents (e.g. caused by induced voltage spikes) by series resistors greater than 7kΩ. Capacity approximately 1000 uF has together C25, C26, C27. Such a capacity is needed, because the power supply cannot provide enough current in a such a short time as the actuator needs for vibration, without a voltage drop on a power supply, therefore are there these capacitors. Pin IN is an input and it defines whether high or low side switch is activated. When pin INH is set to zero, the device goes to a sleep mode. These two pins are essential for a driving of a H-bridge. [19]

An output of IO5 is connected with IO3, which is a Hall-Effect linear current sensor. This component is there in order to sense the current in a H-bridge. Connection Coil2- and Coil2+

are connected to the connector of the actuator. In a Fig. 28 connection of a component ACS711 is shown.

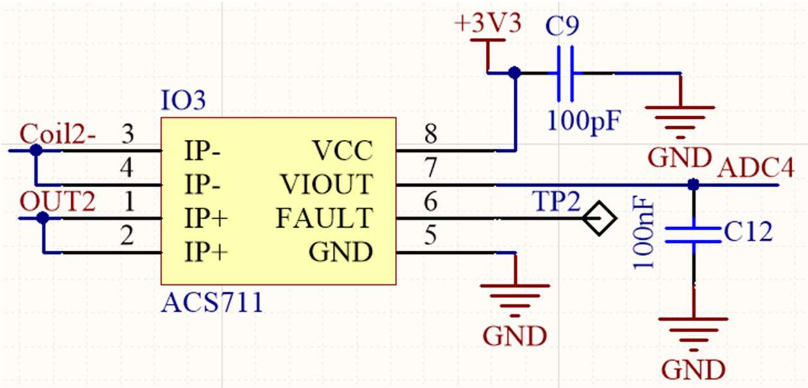


Fig. 28 Hall-sensor ACS711

3.1.3 Sensing circuitry

The component INA212-Q1 has been already introduced in a Chap. 2.6.3. In Fig. 29 integration of this component is shown. Zener diodes are used to protect the component from overvoltage, R29 and R28 are there to limit a current flowing into this IO. Pin IN+ must be connected to supply side of the shunt resistor. Pin IN- is connected load side of the shunt resistor. In case of this actuator, a resistance of the coil is the shunt resistor. A decoupling capacitor is connected as close as possible to the component.

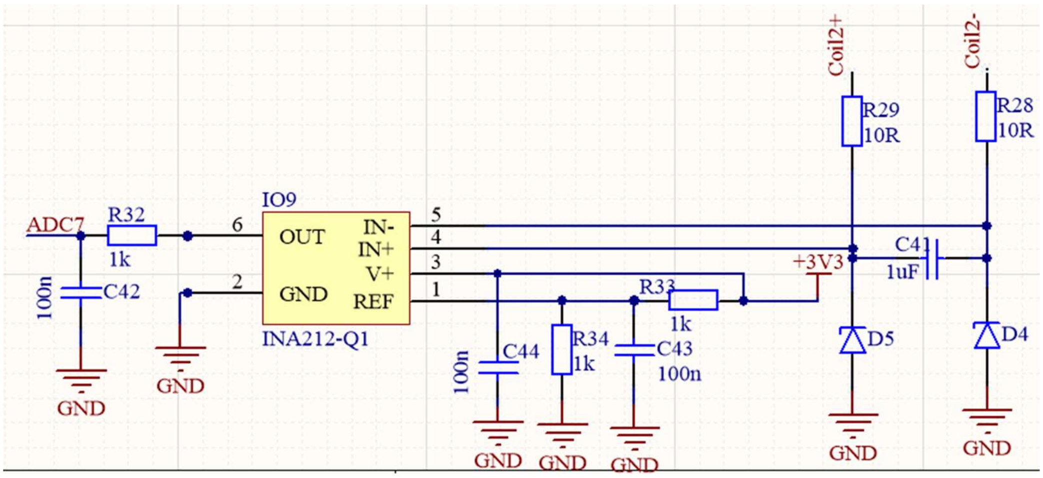


Fig. 29 Sensing circuitry of an induced voltage

3.2 Layout

Signal traces are done with width 10 mil. According to calculation current not more than 4A will flow over this circuit, therefore VCC traces are done 3 mm wide, which is according to the [20] enough for 35 µm thickness of a copper. Net +3V3 is 0.6mm wide and it is powering all ICs in the circuit.

All passive components are used in an SMD design. Resistors and most of the ceramic capacitors and are used in 0603 packages, in order to safe place on a PCB. Some ceramic resistors are used in 0805 design.

The sensing circuitry is placed as close as possible to the connector of the actuator, in order to sense the induced voltage as accurate as possible.

A dead copper on the top and bottom side of a PCB was cut in order to not form antennas and also it is not needed because it has no function.

It has been taken care of, that under crystal is no signal or any other trace, in order not influence the clock signal of the processor.

The ground has been poured on the top and bottom side of the PCB. Those two planes are connected together over many vias in order to keep a current loop as short as possible. Topside of the PCB is shown in Fig. 30.

A thermal plane from a top and bottom side for a components BTN8982TA were placed in order to transfer heat out of the component in order to cool this component down. According to the datasheet [19] such a thermal plane as is more than sufficient as a heat sink for current under 4A. Three PCBs were ordered in order to test different spring of the actuator.

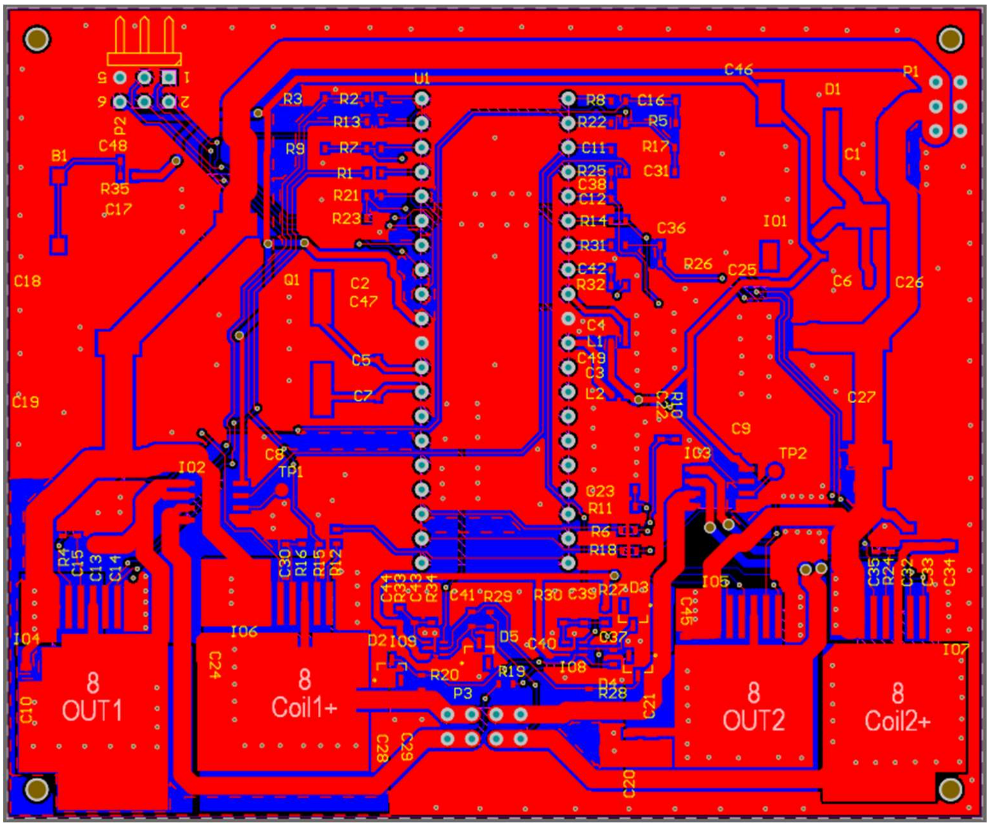


Fig. 30 PCB layout top side view

In a Fig. 31 is shown a raw PCB from a top side. Size of this PCB is 101mm x 84mm. In an Attachment D can be found a PCB bottom side and in Attachment F is a 3D model of the PCB.

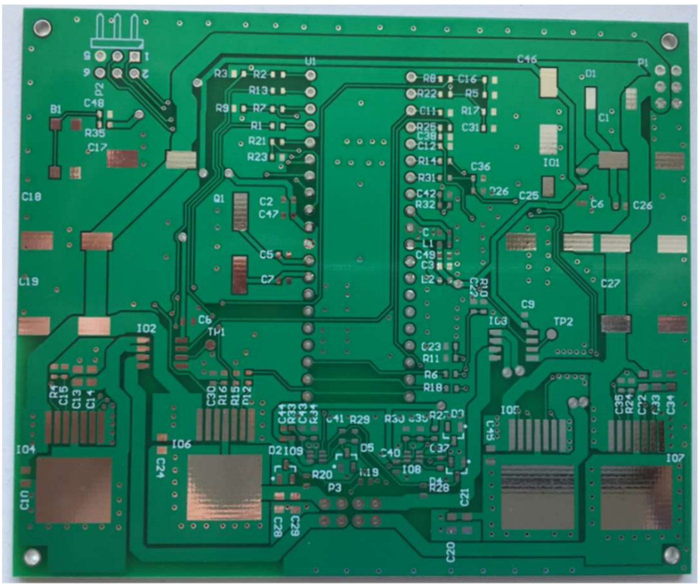


Fig. 31 Manufactured PCB

Component designators were printed on the PCB in order to make manual soldering easier and clearer.

3.2.1 Populated PCB

Components has been mounted on PCB has been without a bigger problem. Mounted PCB is shown on a Fig. 32. In the layout were two small mistakes. A footprint of a voltage regulator and footprint of a Schottky diode was as big as the component itself, therefore soldering of this components were more complicated. Components with a size 0603 were soldered under a microscope. The most demanding soldering part was component INA212-Q1 –IO8, IO9, which is a really small as can be seen in a Fig. 32. Component a Half Bridge BTN8982TA was hard to solder because it has a great thermal pad. A heating plate was used in order to help solder the Half Bridge component. This heating plate was set to a 150 °C. Such a temperature delivered enough heat so that this component could be soldered and at the same time such a temperature will not destroy already placed components and PCB itself.

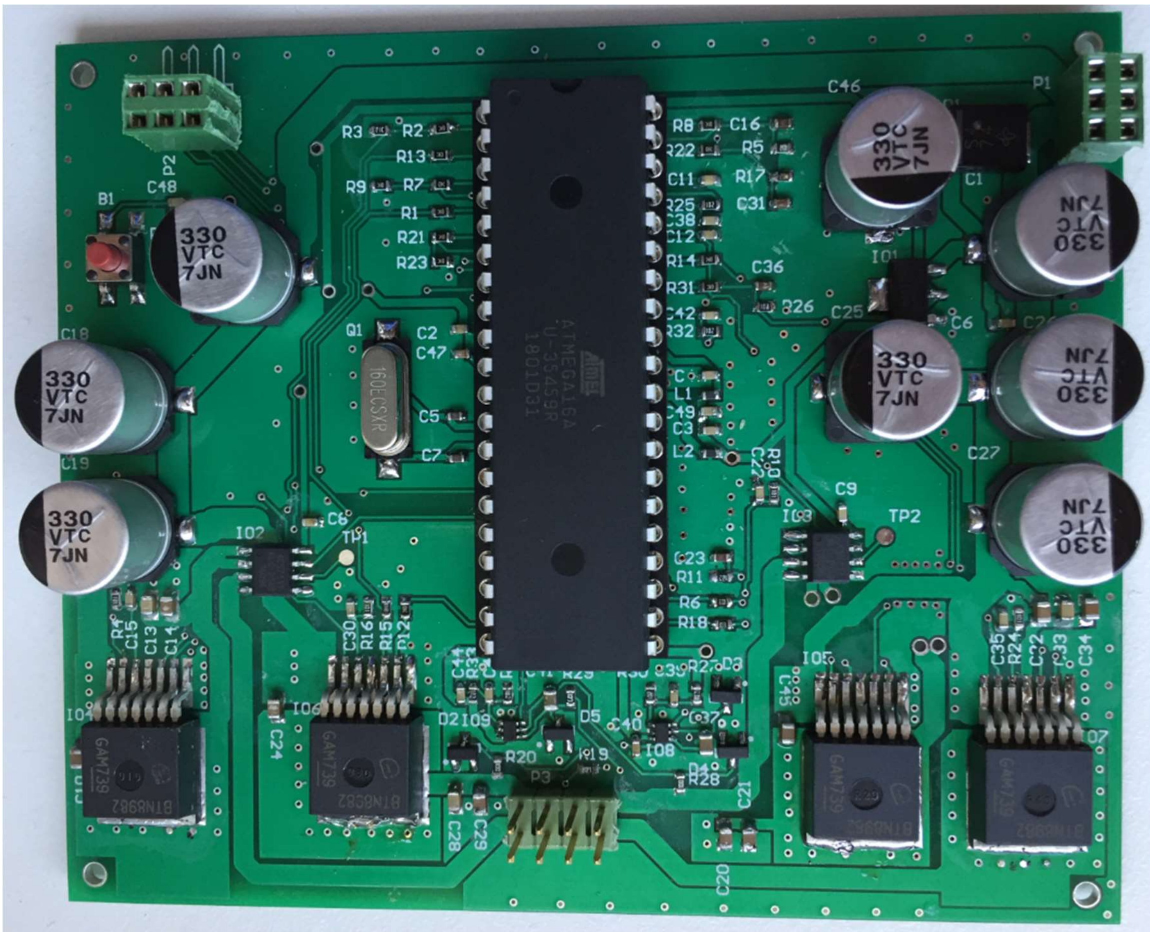


Fig. 32 Populated PCB

The first attempt to revive this board was done without a processor. Firstly, a voltage for the processor and other ICs was measured. It has been found out, that there is no voltage. There was already mentioned the wrong footprint in the layout. I solved the regulator malfunction adding solder to pin parts.

The voice coil actuator and PCB were assembled together. The haptic demonstrator can be seen in an Attachment G.

4 Software design, hardware and software testing and its optimization.

In the block diagram Fig. 2 could be seen the basic function of the haptic demonstrator. Basically what is needed from a software is that an amplified induced voltage will be on a pin of ADC and it is needed to be read. Based on this value the H-bridge will be driven.

This code was written in Atmel Studio 7.0. The complete code can be found in Attachment H. Firstly, were added needed libraries including delay function. Then enable and control pins of a H-bridge were configured. In a Fig. 33 is shown control and enable functions of a H-bridge.

In the next step, an AD converter is initialized in order to read appropriate pin correctly and enable pins of the H-bridge were set high.

```
#define HB1E_1x() PORTB |= 1<< PINB2;  // enable pin of IO5 set to one
#define HB1E_0x() PORTB &= ~(1<< PINB2); //enable pin of IO5 set to zero
#define HB2E_1x() PORTB |= 1<< PINB4;   //enable pin of IO7 set to one
#define HB2E_0x() PORTB &= ~(1<< PINB4);  //enable pin of IO7 set to zero

#define HB1C_1x() PORTD |= 1<< PIND4;   //control pin of IO5 set to one
#define HB1C_0x() PORTD &= ~(1<< PIND4);  //  control pin of IO5 set to zero
#define HB2C_1x() PORTD |= 1<< PIND5;  // control pin of IO7 set to one
#define HB2C_0x() PORTD &= ~(1<< PIND5); //  control pin of IO7 set to zero
```

Fig. 33 Defined enable and control function of a H-bridge

4.1 Driving signal of a H-bridge

According to [1] in order to gain desired vibration from electrodynamic actuators, the frequency used to drive H-bridge must be bigger than 10 kHz. As previously mentioned two actuators were built in order to test the best haptic feedback. In Fig. 34 can be seen driving signal of the actuators. For every half bridge, there is a different driving signal. The frequency of this driving signal is adjustable.

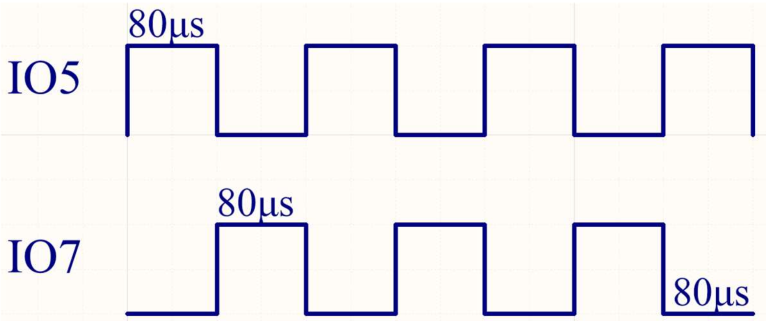


Fig. 34 Driving signal of the actuator

The code was written for the control of a H-bridge as simple as possible. When on ADC is a certain value, first half bridge is set to zero, the second half bridge is set to one, then is used function delay in order the devices stay on wanted position. In this sense, the entire H-bridge is controlled by setting one and zero on control pins as it can be seen in a Fig. 35. The period of this signal was set with a delay function of Atmel Studio.

Code what is shown in a Fig. 35 is already optimized for both versions of the actuator so that it makes desired haptic feedback, which is as nice as to the user possible. The timing of the signal was done only because of my subjective feeling concerning the haptic reception of the vibration.

```
while (1)
{
   ADC_result=ReadADC(7);
   if (ADC_result>520) //at least what value must be on ADC, to start the vibration
                //setting sensitivity of the measuring circuitry
{
         for(int i=0; i<8; i++)
          {
              HB1C_0x();  //set control pin of first half of a h-bridge to zero
              HB2C_1x();  //set control pin of second half of a h-bridge to one
              _delay_ms(0.08); //how long will be the control pins held, before next action happens
              HB2C_0x();  //set control pin of second half of a h-bridge to zero
              HB1C_1x();  // //set control pin of first half of a h-bridge to one
              _delay_ms(0.08); //how long will be the control pins held, before next action happens
              HB1C_0x(); //set control pin of first half of a h-bridge to zero
              HB2C_0x(); //set control pin of second half of a h-bridge to zero
              _delay_ms(0.08); //how long will be the control pins held, before next action happens
          }
         _delay_ms(20);
    }
    }
```

Fig. 35 Driving of a H-bridge

4.2 Software testing

Software in a hex file form was uploaded into a processor over USB-ASP programmer with a help of a program called Extreme Burner 1.4.3.

The vibration without the sensing part was firstly tested in order to verify the functionality of the actuator. In a code in Fig. 33 was changed ADC_result=100 and at the same time was given into an IF condition ADC_result > 101. Basically, to the program was given a value in order that it will think that button was pressed. The device plugged into a power supply and a vibration occurred.

After the first successful experiment, a measuring circuit was tested. One can influence the sensitivity of the measuring circuitry with a change of a value in IF condition. Firstly, I set to the condition IF number 20. This value was too low because actuator started to vibrate on its own. I have figured out after some time of optimizing software, that the best value to set is between 520 and 650.

It measures a quite precise finger touch, but this measuring circuit has its limitation, it cannot measure very soft touch of the finger. An equilibrium between the spring thickness and sensitivity of the measuring circuit must be found. If a sensing circuitry is too sensitive pretty much any movement with haptic demonstrator will lead to its vibration, but when a value for a sensing circuitry would be too high, it would not recognize even stronger finger touch.

4.3 Social research on an appropriate haptic feedback

A pleasant haptic feedback is a very subjective thing. It is not only about the vibration itself which is haptically delivered to the user, but it is also important that along with vibration an unpleasant noise is not present. Because perception of the haptic feedback is a matter of taste, different tests were prepared to the research of an optimal haptic feedback.

4.3.1 Multiple pulse mode of haptic feedback

A longer mode of a haptic feedback reception was tested on 5 people in a hardware department of a Continental Engineering Services company. They were to asked, which of those two actuators had a nicer haptic feedback. Four of five respondent answered that the vibration of an actuator with a thinner spring is nicer and that the actuator with thicker spring does not vibrate when is touched very gently.

From this small research, has been understood that one must do a softer vibration of the thicker spring, because thinner spring is moving on the side and from a mechanical point of view it cannot be further used

4.3.2 Single pulse mode of haptic feedback

A haptic feedback of a single period of a driving signal was examined by 3 respondents including me. Haptic feedback of a thicker spring was nicer for two respondents. Two respondents of this small research were my consultants in a company and they liked this short pulse as a haptic feedback most, therefore such a feedback will be used. A great advantage of this single pulse mode is that during the haptic feedback did not occur unwanted noises.

4.4 Testing of haptic feedback of the actuator with a weight

The vibration of haptic feedback actuator with a thicker spring was tested with a weight of 60g. The weight was aluminum plates, which were glued onto the moving part of the actuator. It was determined, that with an actuator with thinner spring had still a nice haptic feedback, but little weaker.

An old smartphone was glued to the moving part of the actuator to get a feeling on a surface. Vibration on such surface was little weaker, but enough to feel the vibration. The smartphone had a weight 119g. This actuator was designed, in order to develop force up to 5.5N, but it is able to deliver nice haptic feedback with a weight of 119g. From this small experiment, I have figured out, that this actuator can deliver more vibration to the user than actually needed. The force which can the actuator develop does not exactly match the transmitted vibration, therefore further research for the next demonstrator of the force which can the actuator develop and the vibration strength must be further examined.

Because it was observed, that a slightly weaker haptic feedback is given to the user, when some weight is applied, therefore adjustment of the software for haptic feedback is necessary. According to [21] vibration spread differently through different materials such as plastics and metal, however when touch surface is a display, which is made from many materials, it is hard to determinate, what would be the theoretical transmission of the vibration, therefore solution for the testing actuator is to have a little stronger one in order to adapt vibration strength.

4.5 Findings and suggestions for improving of the haptic demonstrator

The problem is that a nicer haptic feedback is gained with a thinner spring which does not fulfill its function, mechanically support the actuator. Both actuators reached a limit of the measuring circuit, because very soft touch of a finger was not recognized, another problem with this sensing is when it is set too sensitive, pretty much any external touch or vibration delivered to the bottom plate of haptic demonstrator or to the table start vibration of the actuator, therefore such a sensitivity of the measuring circuitry is for further use inappropriate. Additional sensors of a finger touch must be used. In the next version of this demonstrator proximity sensor, capacitive foil or smaller, more sensitive coil for measuring induced voltage should be used. Those sensors could be deeper examined and one sensor or combination of more sensors should be used.

This smaller coil has a much thinner wire diameter because is needed that it has as many windings as possible in order to sense induced voltage more precisely. I have determined this relationship from the equation of induced voltage - Eq. (2.33).

4.5.1 Software and layout changes

For a single period of a driving signal there is no need for any changes of the hardware or mechanical parts of the demonstrator with a thicker spring, but sensing part.

The problem occurs with a multiple period mode of the actuator. When a vibration softer is needed it can be achieved by a smaller duty cycle of the PWM for switching the sides of a H-bridge, but in a multiple period mode it causes unpleasant haptic feedback and unwanted noises along with the vibration, it could be also caused because only rectangular shape of the driving signal is used for driving this actuator.

The first thing which can be done is to use a more advanced processor, which supports usage of D/A converter, in order to do smaller pulse in amplitude on the desired frequency. The corresponding software for another processor must be written including usage of D/A converter.

Usage of D/A converter would allow using more advanced driving signal including different shapes. Different shapes of the driving signal can be tested on multiple users in order to gain more objective opinion concerning haptic feedback.

Moving part of the actuator is harder to press due to the greater stiffness of the spring, therefore it is harder to induce voltage with a softer touch. If this actuator is used it will require different sensors for a touch sensing, for example, capacitive foil with a combination of a smaller measuring voice coil. A good idea could be, when the moving part of the actuator would be pressed softly it could give to the user softer vibration and for a stronger vibration induced voltage measuring circuitry could be used.

4.5.2 Mechanical change of the actuator

Instead of using one spring, which connects the static part of the actuator with the moving part. The spring with a thickness 0.3mm will be used because it has been determined, that it has the nicest haptic feedback, but this spring will connect movable and static part of the actuator at least on 4 places, however, this change could influence haptic feedback as well, therefore this solution must be also further examined.

Conclusion

This master thesis fulfilled its purpose. The electrical part of the actuator, a PCB and software for a haptic demonstrator was developed.

Firstly, was explained what a word haptic means and the most common haptic actuators were introduced. In the next step, a block diagram was made, in order to know what will be needed for the whole haptic demonstrator.

The density of magnetic flux in the air gap was calculated and simulated. This simulation was the most important simulation in an actuator development. The ampere-turns has been used here as a variable and based on a change of this value, Lorenz force acting upon coil was determined over a current density. These data were put into a simulation, in order that the Lorenz force has an appropriate value for driving a VCA actuator. Furthermore, the thickness of the wire and the number of turns of the coil were calculated.

The measuring circuitry was simulated in order to determinate if enough voltage in the coil of the actuator is induced and can be used in a PCB design. For this simulation, the induced voltage in the coil was calculated. The driving circuitry was also simulated in order to see the behavior of this circuit. PCB was designed and function of this PCB explained and used components were described. This PCB includes driving and measuring circuitry. The driving software was written so that if the button is pressed, the actuator will vibrate.

Different springs for the actuator were used for two reasons. The first reason was to see a mechanical behavior of the spring and if it is fulfilling its function. The second reason was to determinate pleasantness of the haptic feedback.

It was determined with a help of couple respondents, that a nicer haptic feedback can be achieved by use of thinner spring for multiple period mode. Nevertheless, this spring does not fulfill its function. It does not mechanically support actuator so that it does not move from side to side. The first solution is to do a new mechanical design of the actuator with a thinner spring. The second solution includes usage of D/A converter in order to gain a softer haptic feedback for the actuator with a thicker spring for any touch on a touch surface. Anyhow it was observed that a software must be adapted to the input device used. For both actuators is needed to add additional touch sensor in order that the touch detection becomes more precise.

This master's thesis was a diverse combination of the field of electrical engineering, electronics, mechatronics and embedded software. Despite several obstacles in this master´s thesis, I enjoyed working on this interesting topic. I have gained a lot of knowledge on this subject, therefore, I would be eager to continue in the further development of this device.

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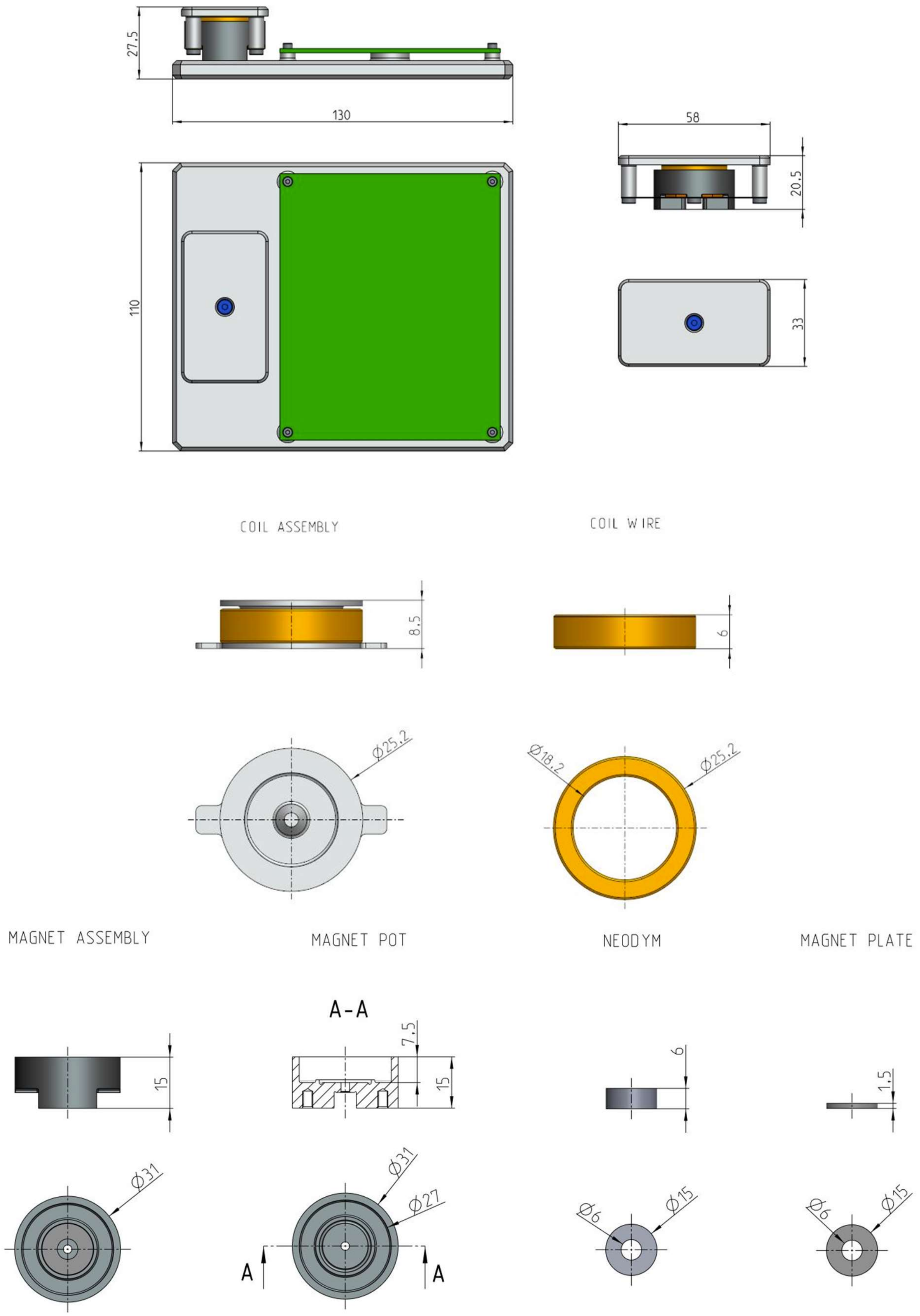
Attachments

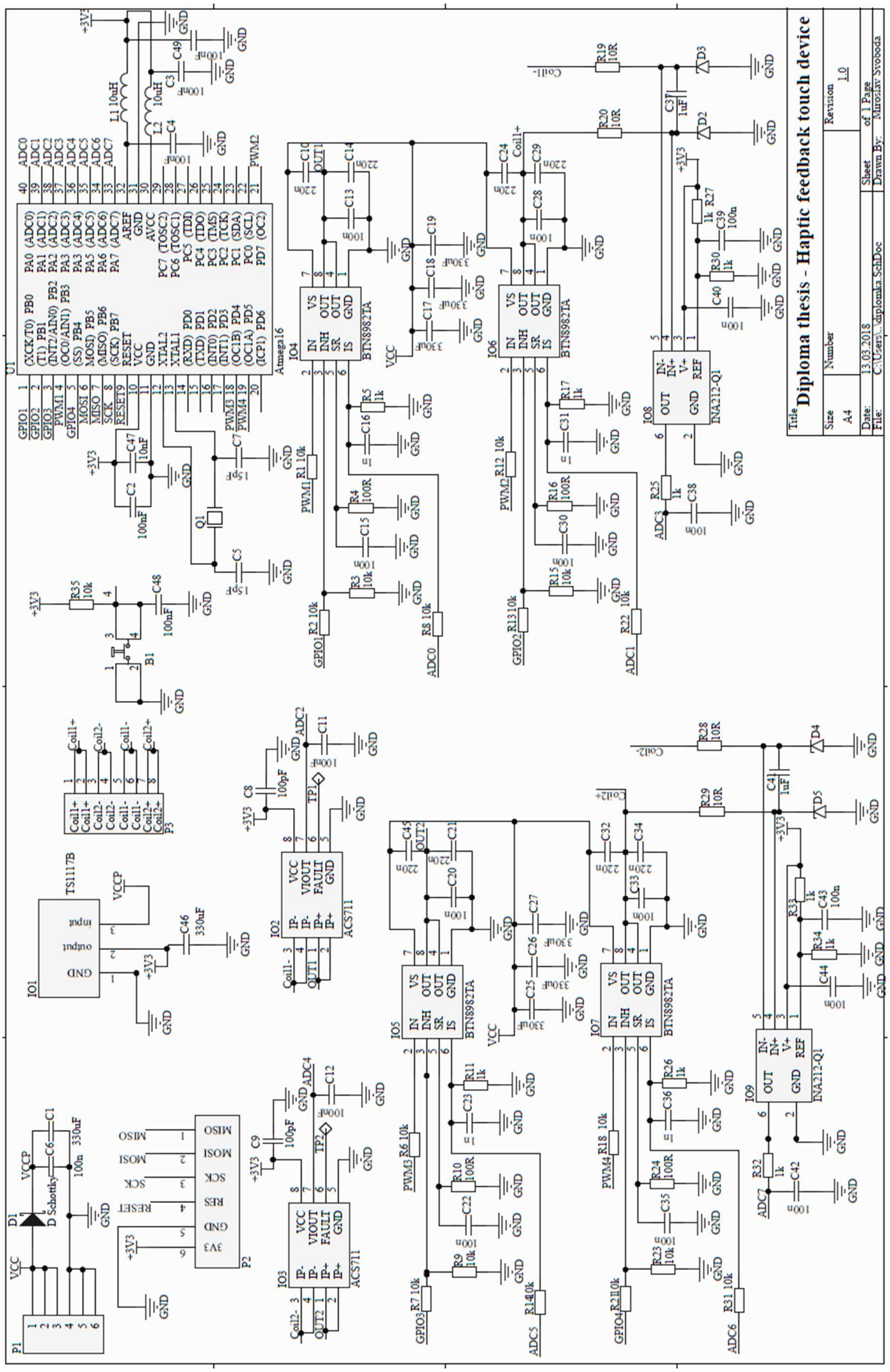
Attachment A– BOM of the actuator

Name	Material/Manufacturing	Amount *
Coil assembly		
Coil bobbin	Aluminium	3
Coil holder	Aluminium	3
Wire	Cu	-
Sunk screw	M3x5, not magnetic	3
Magnet assembly		
Metal pot	Steel	3
Neodymium Magnet	supermagnete.de, R-15-06-06-N	3
Magnet plate	Steel	3
other components		
Spring (haptic feedback)	Steel	3
Cylindrical screws	M3x5 , not magnetic	20
Cylindrical screws	M3x7, not magnetic	10
Bottom plate	Stainless steel	3

Attachment B – Dimensions of the actuator



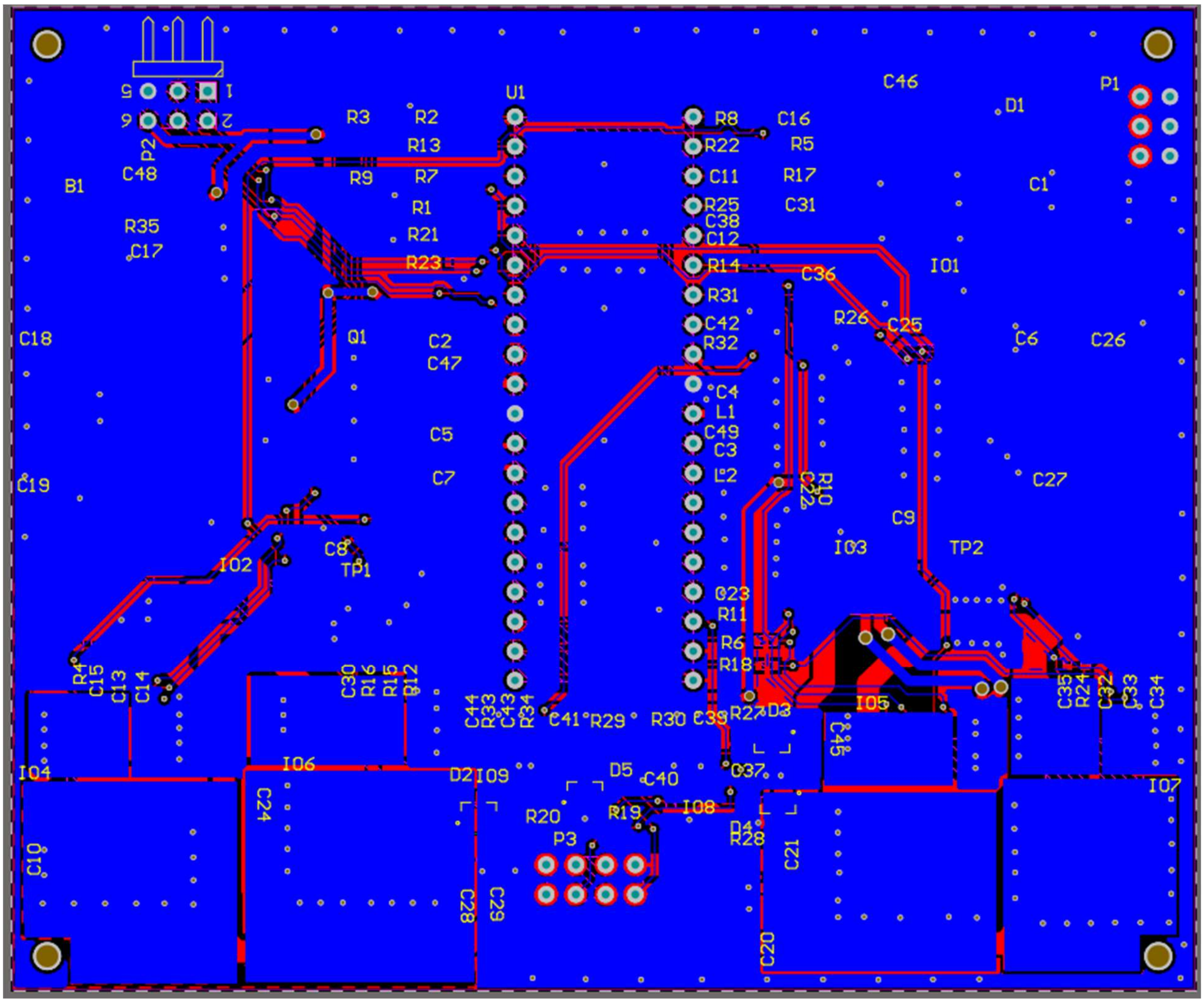
Attachment C – Schematics



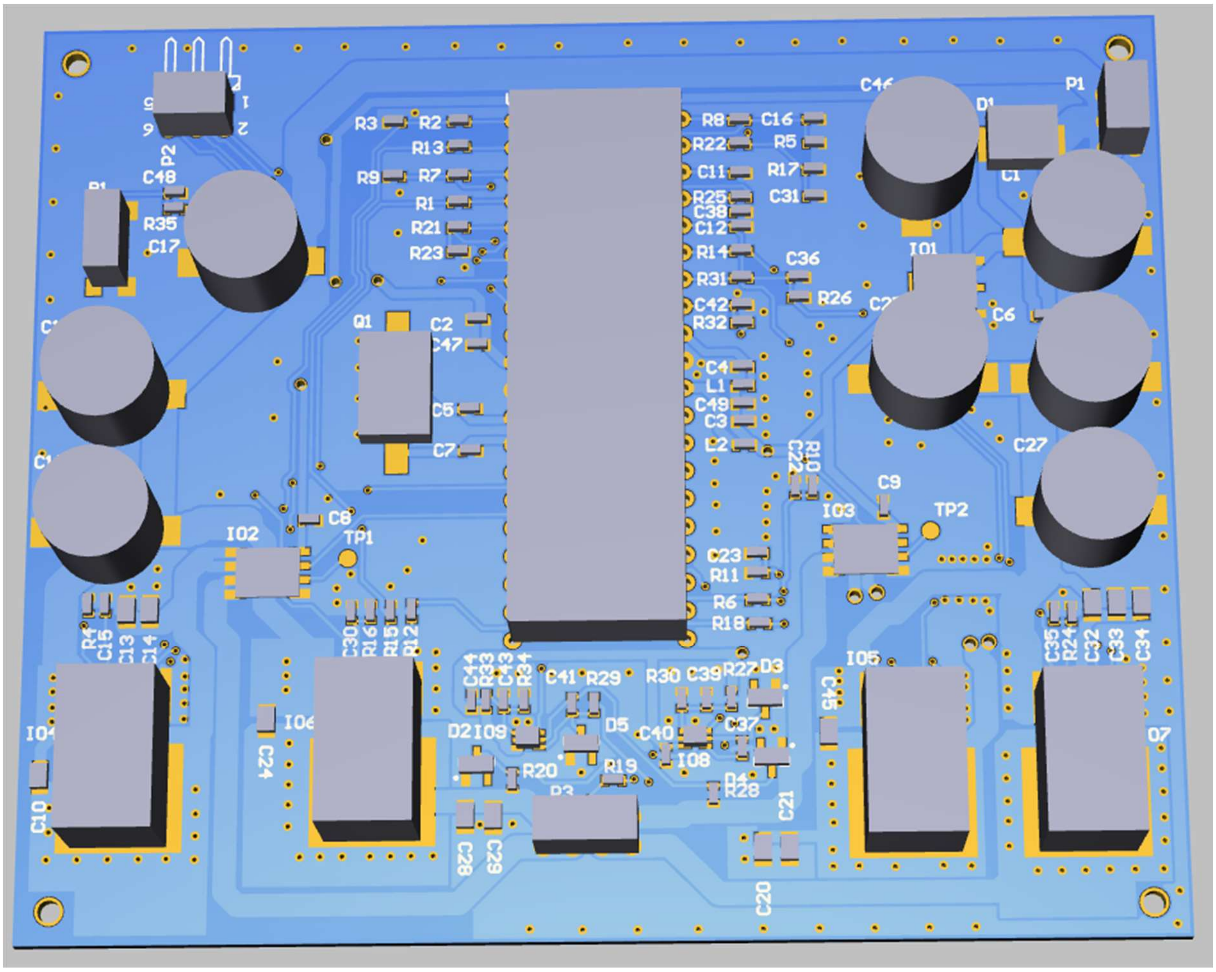
Attachment D – Bill of material of the PCB

Component	Designator	Description	Quantity
ATMEGA16A-PU	U1	processor	4
HC49USSMD	Q1	crystal 16Mhz	4
BTN8982TA	IO5, IO7, IO4, IO6	half H-bridge	15
socket PDIP 40		procesor socket	3
TS1117B	IO1	3V3 regulator	4
BZX84C	D2, D3,D4,D5	zener´s diode	15
ACS711	IO2,IO3	current-measuring circuit	10
330uF, 35V	C?	condensator	28
TD-03XA-T SMD	B1	microswitch	5
SMC/DO214AB	D1	schotky diode	5
INA212AQDCKRQ1	IO9, IO8	induced voltage sensing	10
Ferrit bead	L1, L2	ferite bead	10

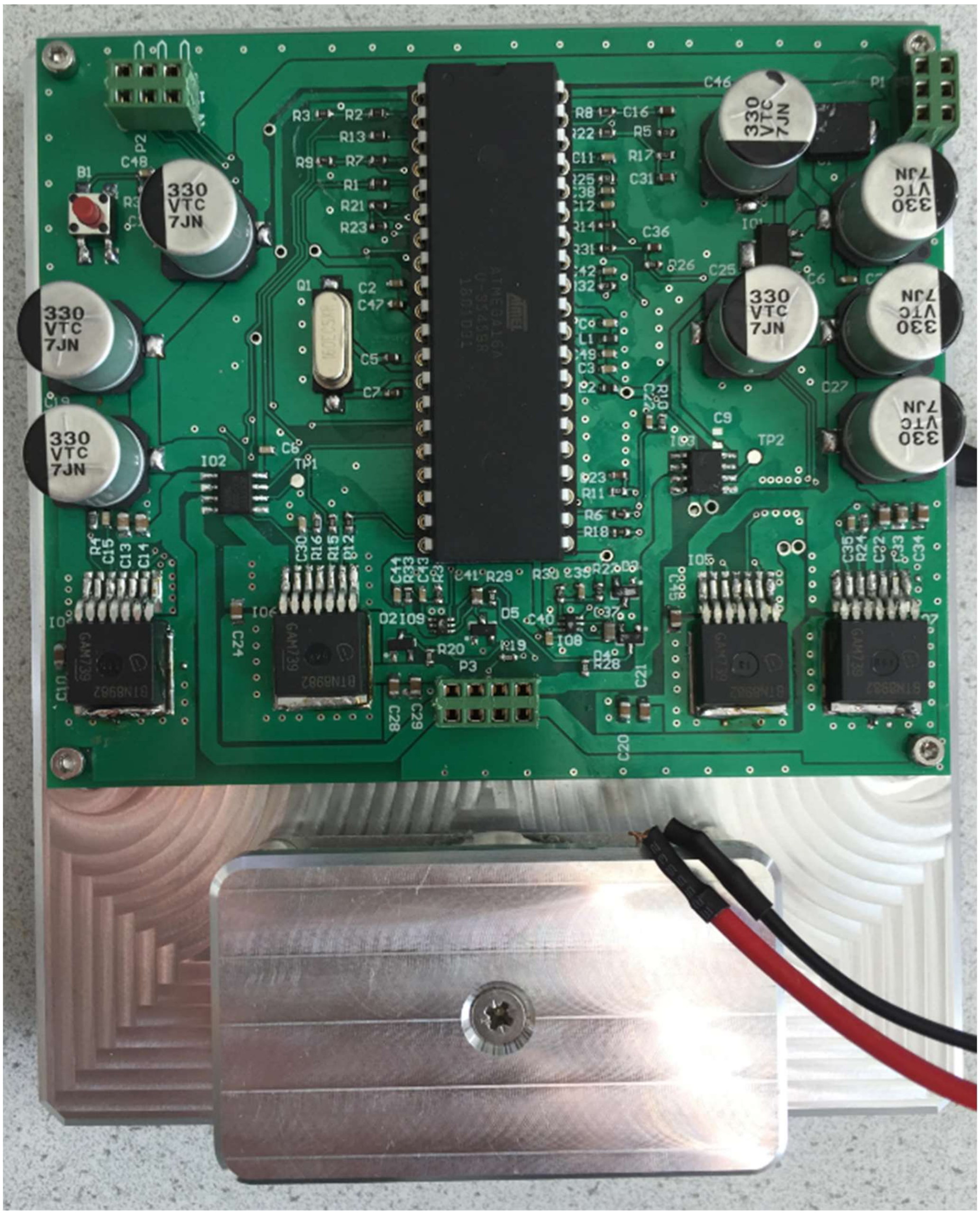
Attachment E – PCB BOTTOM SIDE



Attachment F – 3D MODEL of the PCB



Attachment G – Haptic demonstrator



Attachment H - Software

```
#include <avr/io.h>

#include <avr/io.h>
#define F_CPU 16000000UL
#include <util/delay.h>
#include <avr/interrupt.h>
#include <stdio.h>                /* Include std. library file */

#define HB1E_1() PORTB |= 1<< PINB0;  //enable pin of IO4 set to one
#define HB1E_0() PORTB &= ~(1<< PINB0);  //enable pin of IO4 set to zero
#define HB2E_1() PORTB |= 1<< PINB1;   //enable pin  of IO6 set to one
#define HB2E_0() PORTB &= ~(1<< PINB1);  //enable pin of IO6 set to zero

#define HB1C_1() PORTB |= 1<< PINB3;   //control pin of IO4 set to one
#define HB1C_0() PORTB &= ~(1<< PINB3);  //control pin of IO4 set to zero
#define HB2C_1() PORTD |= 1<< PIND7;  //control pin of IO6 set to one
#define HB2C_0() PORTD &= ~(1<< PIND7); // control pin of IO6 set to zero

#define HB1E_1x() PORTB |= 1<< PINB2;  // enable pin of IO5 set to one
#define HB1E_0x() PORTB &= ~(1<< PINB2); //enable pin of IO5 set to zero
#define HB2E_1x() PORTB |= 1<< PINB4;   //enable pin of IO7 set to one
#define HB2E_0x() PORTB &= ~(1<< PINB4);  //enable pin of IO7 set to zero

#define HB1C_1x() PORTD |= 1<< PIND4;   //control pin of IO5 set to one
#define HB1C_0x() PORTD &= ~(1<< PIND4);  //  control pin of IO5 set to zero
#define HB2C_1x() PORTD |= 1<< PIND5;  // control pin of IO7 set to one
#define HB2C_0x() PORTD &= ~(1<< PIND5); //  control pin of IO7 set to zero

int main (void)
{

       InitADC();
       int ADC_result ;
       HB1E_1();  // turn on of half of H-bridge, left side
       HB2E_1(); // turn on second half of a H-bridge, left side
       HB1E_1x() // turn on of half of a H-bridge, right side - actually used
       HB2E_1x() // turn on of second half of a H-bridge, right side - actually used

       DDRB=0xFF; // set pins as a output, ddr, than port
       DDRD=0XFF; // set pins as a output

while (1)
{
ADC_result=ReadADC(7);
if (ADC_result>520) //at least what value must be on ADC, to start the vibration
                     //setting sensitivity of the measuring circuitry
       {
          for(int i=0; i<1; i++)
       {
       HB1C_0x();  //set control pin of first half of a h-bridge to zero
       HB2C_1x();  //set control pin of second half of a h-bridge to one
       _delay_ms(0.08); //how long will be the control pins held, before next action
                           happens
       HB2C_0x();  //set control pin of second half of a h-bridge to zero
       HB1C_1x();     // //set control pin of first half of a h-bridge to one

       _delay_ms(0.08); //how long will be the control pins held, before next action
       HB1C_0x(); //set control pin of first half of a h-bridge to zero
        HB2C_0x(); //set control pin of second half of a h-bridge to zero
       _delay_ms(0.08); //how long will be the control pins held, before next action
```

```
        }
        _delay_ms(20)
        }
        }
        }

void InitADC()
{
        ADMUX &= ~(1 << ADLAR); //margin right
        ADMUX &= ~(1 << REFS0);
        ADMUX &= ~(1 << REFS1); // Set the prescaler to clock/128 & enable ADC
        ADCSRA |= (1 << ADPS2) | (1 << ADPS1) | (1 << ADEN);
}

int ReadADC(int ch)
{
        ch &= 0b00000111; //load a channel
        ADMUX = (ADMUX & 0xF8)|ch; // delete last bits and ch

        ADCSRA |= (1 << ADSC);
        while (ADCSRA & (1 << ADSC));

        return ADC;
}
```