Design of an automated test setup for power-controlled nerve stimulator using NFC for implantable sensors

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Abstract

Electrical stimulation on nerves is a relatively new area of research and has been proved to speed up recovery from nerve damage. In this work, the efficiency and stability of antennas integrated on printed circuit boards provided by the department of electrical engineering are examined. An automated test bench containing a step motor with a slider and an Arduino is created. Different setups were used when measuring on the boards, which resulted in that the largest antenna gave the most stable output despite the distance between transmitter and receiver. The conclusion was that the second best antenna and the smallest one would be suitable as well, and the better choice if it is to be implemented under the skin.

A physical setup consisting of LEDs, an Arduino, a computer, and a function generator was created to examine the voltage control functionality, where colored LEDs were lit depending on the voltage level. The functionality was then implemented in a circuit that in the future shall be integrated on the printed circuit board. To control high voltages a limiter circuit was examined and implemented. The circuit was simulated and tested, with a realization that a feature covering voltage enlargement is needed for the future.

Acknowledgments

Abbreviations

AC	Alternating current
ASIC	Application Specific Integrated Circuit
DC	Direct current
EH	Energy harvester
ES	Electromagnetic stimulation
GUI	Graphical User Interface
HF	High frequency
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
LED	Light emitting diode
NFC	Near-field communication
NPN	Negative-positive-negative
PCB	Printed circuit boards
PNP	Positive-negative-positive
PNS	Peripheral nerve stimulation
PTx	Transmitted power
RF	Radio frequency
RFID	Radio-frequency identification
Rx	Receiver
SCS	Spinal cord stimulation
SSF	Swedish Foundation for Strategic Research
STINT	The Swedish Foundation for International Cooperation in Research and Higher Education
Tx	Transmitter
USB	Universal serial bus
WPT	Wireless power transfer

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1 Introduction

The Department of Electrical Engineering (ISY), at Linköping University, collaborates with the University Hospital to research on how to heal damaged nerves by inducing electrical impulses in them. This thesis work will continue on previous years thesis work and related research in order to make improvements on the hardware ISY has developed. In the following chapter an introduction to the project is given. The motivation, aim, research questions, delimitations, and the outline of the project is covered in this chapter.

1.1 Aim

The aims of the thesis project are specified below.

- Evaluate the existing boards (see section 4.1), to get a deeper understanding of how the printed circuit boards work and see how efficient they are in different environments.

- Create a test bench where the distance between transmitter and receiver can be changed automatically.

- Compute graphs that show how the relationships between P_{in}/P_{out} are for wireless power transfer, over different distances.

- Design a solution that can keep a constant power at the output at the receiver for different distances between the printed circuit boards.

- Get a deeper understanding how electronic pulses can stimulate a nerve in order to motivate the thesis project.

The delimitations in section 1.3 below restrict the aims of this project.

1.2 Research questions

The research questions that will guide the project are listed below.

- What power from the transmitter is required from the sender to guarantee X mA stimulation through a nerve when considering different distances?

- What kind of antenna is more efficient regarding power transfer?

- How can the existing printed circuit board become more efficient?

- What components are required to reach more efficiency?

- How does the frequency relate to how much power that is sent into a nerve?

The delimitations in section 1.3 below set a bound on the problems specified above.

1.3 Delimitations

In the following section, all the delimitations are listed.

- No human tissue is used.

- The maximum distance between receiver and transmitter is 10 cm.

- The power is limited by the transmitter.

- A computer shall be used for measurements. A phone can be used for simpler tests.

- The type of antennas/coils that will be analyzed are flat rectangular ones on a printed circuit board.

- The voltage control solution will not be implemented in a chip on a printed circuit board.

The delimitations are specified to illustrate, specify, and guide the project.

1.4 Outline

In chapter 1 an introduction of the thesis project is presented. The research questions, aims, and delimitations are specified.

In chapter 2 the background of the project is specified. It contains information about nerves and their regeneration abilities, NFC and the standards that are used, and wireless power transfer.

In chapter 3 the theory for the project is presented. The chapter contains information about nerve stimulation, the tolerance level, mutual inductance for coils, confidence interval, information about MOSFET transistors, energy harvesters, and limiter circuits.

In chapter 4 the previous work is presented as well as the boards that shall be used when evaluating the antennas.

In chapter 5 the method of the project is presented. It contains an evaluation of the previous work, both a theoretical and practical. The test setup is explained and how the measurements is carried out as well as the different types of test setups. The last part contains the voltages control development in both a physical setup as well as a circuit design.

In chapter 6 the results from the different tests in chapter 5 are presented. Graphs, tables, and simulation results are presented.

In chapter 7 the discussion of the result from chapter 6 is presented.

In chapter 8 the conclusions are drawn and answers to the research questions is presented.

In chapter 9 ideas for future work are discussed and proposed. The theoretical and practical issues are discussed from a wider perspective.

1.5 Contribution

The thesis project has been done by two students, Amanda Aasa and Amanda Svennblad, there is therefore a need of clarification for what each person has done, this can be seen in table 1.

Amanda Aasa	Amanda Svennblad
Programmed the Tx board in Python.	Theoretical calculations in Matlab.
Created a physical setup for the voltage controlled feature.	Programmed the step motor to the test bench.
Implemented the voltage controlled feature in Cadence.	Made all the graphs from the evaluation of the boards.

Table 1: Contribution from each group member. The contributions are listed under each name in the columns.

2 Background

The thesis project is based on a research project at the University Hospital in Linköping, the department of Electrical Engineering, and the Laboratory of Organic Electronics at Linköping University. The projects have been funded by Vinnova, Swedish Foundation for Strategic Research (SSF), and The Swedish Foundation for International Cooperation in Research and Higher Education (STINT). The aim of the project is to improve the healing process of damaged nerves. The means to accomplish this is by implementing a voltage control and determine which antenna should be used in/on the ASIC boards. In this chapter is the information about nerve generation, NFC, and WPT presented.

2.1 Nerve

Nerve cells, also called neurons, are responsible for inter-cellular communication. Neuron appearance and function differ depending on where a nerve is located. In Figure 1 the structure of a typical neuron is illustrated.
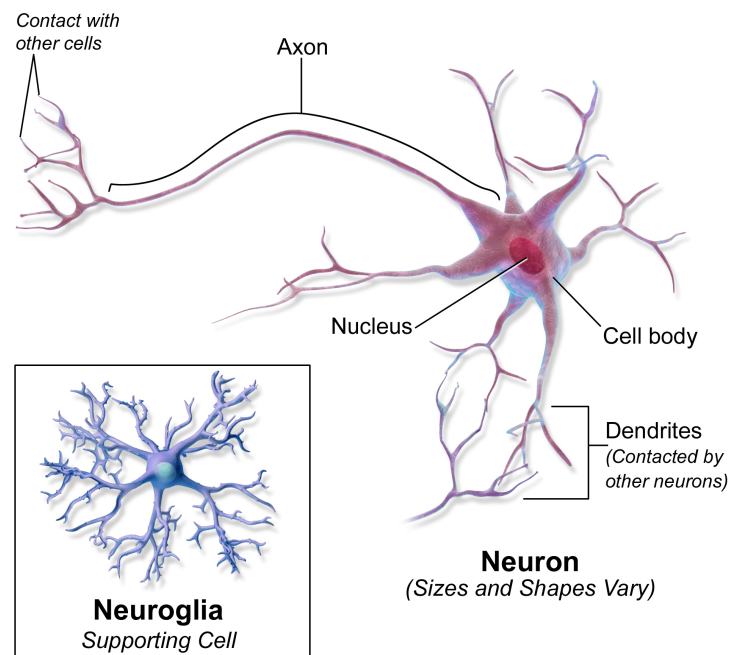
Figure 1: An image of nerve tissue. Source [1] @2014 by Blausen.com staff, used with permission

The neurons transmit information through chemical communication. The dendrites primary task is to receive chemical signaling molecules from other neurons. The message is translated and transferred as an electrical pulse through the axon. When the electrical pulse reaches the axon terminals, the terminal emits chemicals. The neurons that are nearby will collect the chemicals. The message is transmitted from neuron to neuron until the information has reached the brain.[2]

Figure 2 shows the cross section of a nerve where the axons placement can be seen. A nerve is a connection between muscles/organs and the central nervous system. If nerves are damaged, the connection can be broken. The consequences of a lost connection may cause paralysis and lost feeling in the affected body part.[2]
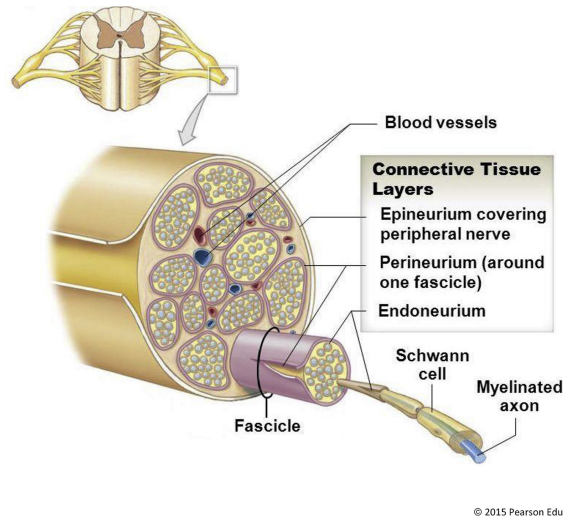
Figure 2: Cross section of a nerve. Source [3] @2019 used with permission

2.1.1 Regeneration

When trauma occurs that is so severe that nerves have been cut, nerves are sewn back together to help the healing process. The regrowth of the axon is 1-2 mm/day, despite optimal nerve repair, which is slow. There is not only the axon that has to be repaired and regrown, but the surrounding tissue as well. The period for regeneration of damaged nerves is long, a few years depending on the trauma and damage. For example, if a wrist got nerve injuries it would entail a distance of around 100 mm, and it would take 50-100 days for each axon to regrow to reach several hand muscles. If an injury would occur at the brachial plexus (at the shoulder) the regrowth of the axon would take more than two to three years. [4].

A study on humans has shown that if a damaged nerve would be stimulated by electrical pulses, the healing process is faster compared to a nerve that does receive any treatment [5]. A clinical pilot study was carried out on 21 patients with carpal tunnel syndrome [6]. Electrical stimulation was applied for one hour at a nerve located near the wrist which showed an accelerated axon regeneration [6]. Similar results can be seen when studies have been carried out on rats [7], [8]. The studies that have been finalized are carried out during a short period of time, and the long term effects of nerve stimulation have as of May 2021 not been disclosed.

2.2 Near-field communication

Near-field communication (NFC) was launched by Sony, Philips, and Nokia in March 2004, by the foundation of the NFC Forum [9]. NFC is a contact less communication between two devices with a distance limitation of 10 cm [10]. NFC makes it possible for users to access content, services, make transactions, and connect devices [9], [10].

Products that are NFC-based should be manufactured according to certain standards that is compatible within the industry field [11]. NCF operates at 13.56 MHz under the ISO/IEC 14443, ISO/IEC 18092, and FeliCa standards [12].

2.2.1 NFC standards

The standards have different characteristics and are adapted for different assignments. For NFC there are a set of rules and protocols which are listed below:

ISO/IEC 14443 is often used for contactless payments, electronic access control, etc [13]. It has four parts [14] that comprise the standard:

- **Part 1** is responsible for the physical characteristics of the card/tag such as temperature, damage tolerances, and size.

- **Part 2** describes the radio frequency power and signal interface.

- **Part 3** is the initialization and anti-collision regulations.

- **Part 4** is responsible for high-level data transmission.

ISO/IEC 18092 is similar to ISO/IEC 14443, the difference is step 4. In ISO/IEC 18092 step 4 contains two communication modes, passive and active. This allows for a peer-to-peer mode which makes it possible for an NFC device to communicate with other NFC devices. The two modes make it possible for the NFC to have three operation modes [14]:

1. **Read/Write:** A device with NFC enabled can read or write to any tag that is supported by the NFC standard. The data that is written or read requires a standard NFC data format.

2. **Peer-to-Peer:** Two devices equipped with NFC can transfer data, for instance, the devices can share Bluetooth or a WiFi.

3. **Card-Emulation:** A device can act as a tag towards other readers.

FeliCa is another protocol for contactless cards and is owned by Sony [15].

2.2.2 Wireless power transfer

Wireless power transfer (WPT) can be found in applications such as satellite communications and radio frequency identification (RFID) tags. To achieve high power WPT, inductive coupling is used. Inductive coupling was invented by Nikola Tesla. [16]. In Figure 3 a block diagram is shown, where a WPT system based on inductive coupling is illustrated. Respectively in the transmitter (Tx) and receiver (Rx) there are two inductive coils, source, and load, connected. The wireless power transfer is transmitted to the receiver through a coupled magnetic field. From the transmitter, energy is harvested to provide the load. [17]
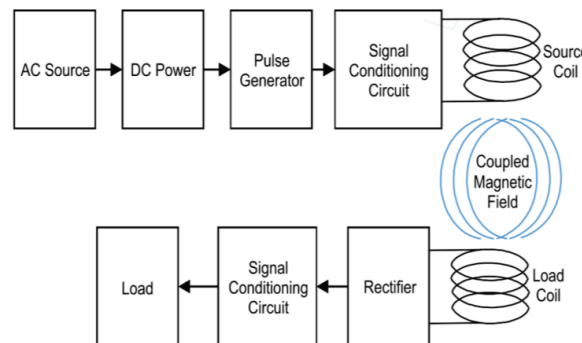
Figure 3: Figure of inductive coupled WPT system. Source: [17] @2018 used with permission from publisher

When power is transmitted from the coil at the sender side (Transmitter, Tx) to the coil on the load side (receiver, Rx), an electromagnetic wave is created by the first coil. When current flows through the first coil a magnetic flux is produced. The magnetic flux will move to the second coil where it will be cut, which means that an electric current will induce. [18]

5

3 Theory

The fundamental theory behind how a nerve responds to current and electrical stimulation, equations to calculate the mutual inductance in coils, and the efficiency between Tx and Rx is provided in this chapter. Information regarding a confidence interval, MOSFETs, energy harvesters, and limiter circuits is covered as well.

3.1 Electrical Nerve Stimulation

Electrical nerve stimulation uses an electrical current to treat chronic pain. There are two types of electrical nerve stimulation, peripheral nerve stimulation (PNS) and spinal cord stimulation (SCS). It uses low electrical current from a small pulse generator which is sent to a nerve or spinal cord, to reduce pain. [19]. The electrical nerve stimulation method is also used to speed up the regrowth of nerves.

3.1.1 Tolerance

Due to health considerations the voltage, power, and current need to be controlled to not damage a nerve and surrounding tissue. Previous tests performed on the peripheral nerve of rats have used the same stimulation settings [20]. The settings is set to one h stimulation at 20 Hz with 0.1 ms pulse widths [20].

A circuit that has been used when doing tests on male Wistar rats uses a 1.5 V battery and a 1.3 MΩ resistor. The circuit was designed to deliver a constant continuous current of 1 μA. [8].

A clinical study on 21 patients that has carpal tunnel syndrome used electromagnetic stimulation (ES) to investigate the regrowth of the axon [21]. The settings for the ES in the study were gradually increasing to a maximum of $4 - 6$ V and $10 - 80$ μs (in pulse width) with a continuous frequency of 20 Hz and a maximum of one hour at a time [21].

3.2 Mutual inductance

The setup for a nerve stimulation can be seen in Figure 4. The outside coil generates the magnetic flux that will contribute to a mutual inductance to the inside coil. The intensity from the field reduces when the distance between the coils increases. The Tx and Rx that are used in this project are rectangular or square antennas.
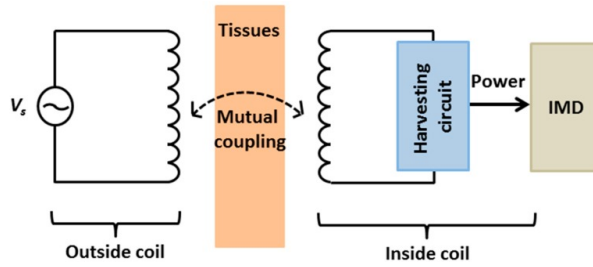
Figure 4: Inductive coupling overview. Source [22] @ 2015 used with permission

The mutual inductance is calculated for when the antennas are centered in a parallel position. The length of the Tx sides are $2a$ and $2b$, measured at the outer turn of the coil. The sides of the Rx are $2c$ and $2d$, and z is the distance between the antennas. The Tx has four side segment (AB, AD, DC, CB). The setup for the antennas can be seen in Figure 5.
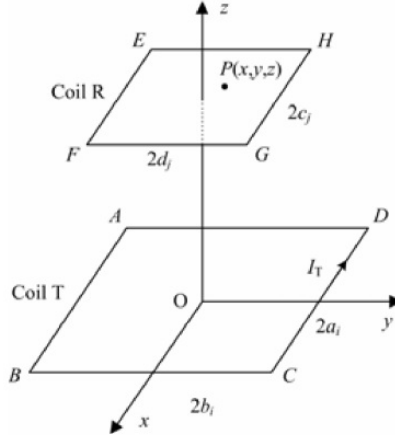
Figure 5: Two single turn rectangular coils, that are centered in a parallel position, with a distance z between them. Source [23] @ 2014 used with permission

The total mutual inductance between two rectangular/square coils are

$$M = \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} M_{i_j}, \tag{1}$$

where N_T and N_R are the number of turns on the Tx and Rx respectively. M_{ij} is the mutual inductance between the $j:th$ coil on Rx and the $i:th$ coil on Tx.

M_{ij} can be calculated as $M_{ij} = M_{CD-z} + M_{AB-z} + M_{DA-z} + M_{BC-z}$, where z is the distance between the boards, and all the side segments from the Tx need to be included. M_{CD} is calculated as

$$
\begin{aligned}
M_{CD-z} = \frac{2\mu_0}{\pi} \Bigg[& \sqrt{(bi+dj)^2 + (ai+cj)^2 + z^2} - \sqrt{(bi+dj)^2 + (ai-cj)^2 + z^2} \\
& + \sqrt{(bi-dj)^2 + (ai-cj)^2 + z^2} - \sqrt{(bi-dj)^2 + (ai+cj)^2 + z^2} \\
& - (ai+cj)\operatorname{arctanh} \frac{ai+cj}{\sqrt{(bi+dj)^2 + (ai+cj)^2 + z^2}} \\
& + (ai+cj)\operatorname{arctanh} \frac{ai+cj}{\sqrt{(bi-dj)^2 + (ai+cj)^2 + z^2}} \\
& - (ai-cj)\operatorname{arctanh} \frac{ai-cj}{\sqrt{(bi-dj)^2 + (ai-cj)^2 + z^2}} \\
& + (ai-cj)\operatorname{arctanh} \frac{ai-cj}{\sqrt{(bi+dj)^2 + (ai-cj)^2 + z^2}} \Bigg].
\end{aligned}
\tag{2}
$$

The magnetic flux for the other three segments (AB, BC ,DA) is calculated in the same manner. Symmetry of the coils gives $M_{CD} = M_{AB}$ and $M_{DA} = M_{BC}$. Equation 2 is used to calculate M_{DA} and M_{BC}, where $a = b$ and $c = d$. [23]

The coupling factor is a number between zero and one, and is the efficiency between the coils. The coupling factor can be written as

$$k = \frac{M}{\sqrt{l_t \cdot l_r}}, \tag{3}$$

where l_r and l_t is the inductance for the Rx and the Tx. [24]

3.3 Efficiency

The efficiency between Rx and Tx can be written as

$$\eta = \frac{P_{out}}{P_{in}}, \tag{4}$$

where P_{in} is the power from the Tx and P_{out} is the power at the measured output.

3.4 Confidence interval

An interval I_θ with confidence level $1 - \alpha$ covering θ is called a confidence interval. The confidence level $1 - \alpha$ can be chosen freely but for the confidence interval to be useful the value is often chosen to be 0.95, 0.99 or 0.999. This means that there is a 5%, 1% respectively 0.1% chance to make an incorrect statement.[25]. Figure 6 shows an example of how a confidence interval is used. In this Figure there is a bar chart which shows an observed means and the red line segments is the confidence interval around them [26].
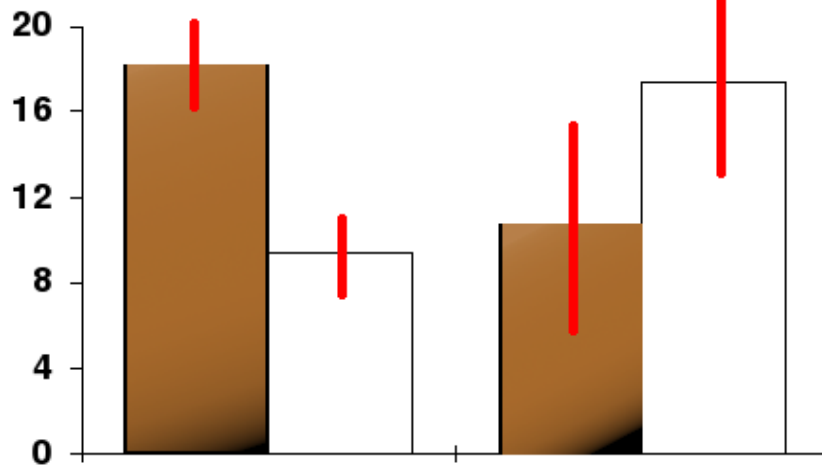
Figure 6: Bar chart where the top ends of the brown segments indicates the observed means and the red line segment shows the confidence interval [26]

3.5 MOSFET

A CMOS uses two types of MOSFETs, NMOS and PMOS, to create logic functions. The two MOSFETs have different switching characteristics. The NMOS is ON if the condition $V_{gs} > V_{Tn}$ is fulfilled. For the NMOS to be OFF the condition switches to $V_{gs} < V_{Tn}$. For the PMOS to be ON the condition is $V_{sg} > |V_{Tp}|$. The condition for the PMOS to be OFF is $V_{sg} < |V_{Tp}|$. [27]

3.6 Bipolar junction transistor

A bipolar junction transistor is a three layer semiconductor. There are two types of bipolar junction transistors PNP and NPN. There are three terminals and are denoted emitter E, base B, and collector C. The width of the base need to be smaller than the diffusion length of the minority charge carriers in the base. If this condition is satisfied the transistor can be used as an amplifier and with other conditions it can be used as a controlled switch. The transistor uses a small current at one of the terminals to control a much larger current flowing through the other two terminals, to work as an amplifier or switch. [28]

3.7 Energy Harvester

An energy harvester (EH) takes the energy that the Rx collects from the magnetic flux from the Tx. The EH converts the received energy and provides an analog output that can be used in the electrical circuit. The EH includes an ADC. The EH starts when it receives energy that is higher than a threshold value. The output from the EH is a constant voltage, if the received energy go below the threshold value, the output from the EH decreases linearly. [29]

3.8 Limiter circuit

A receiver limiter, also called a limiter, protects the receiver from large input signals. The limiter allows the receiver to function normally despite the large input signals. [30] Figure 7 shows a voltage limiter circuit on a transistor level that uses the output from the rectifier. The output voltage from this limiter circuit is controlled to 2 V. [31] The limiter contains three bipolar junction transistors marked NPN2 and four MOSFET transistors.
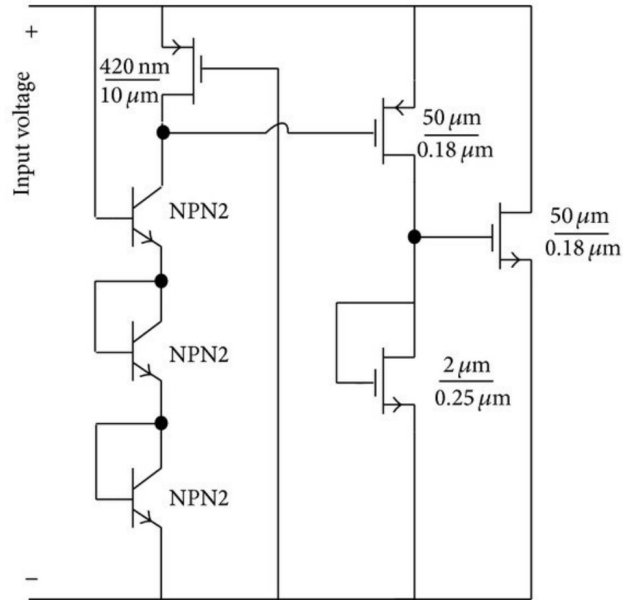
Figure 7: A voltage limiter circuit [31]

4 Previous work

To support this thesis work knowledge from previous work needed to be gathered. Information will be retrieved from Samir G. Sabah's [11] and Guillem Erráez Castelltort's [13] thesis reports from previous years. Two of the ASIC boards that are to be investigated are built by the supervisor Yonatan Kifle. In this chapter, the boards used in the project will be presented in terms of size and what type of EH chip there is.

4.1 Existing boards to be evaluated

The boards contain an ASIC chip which is of interest, when investigating the boards. Several of the boards have similar functionality but the size of the antenna is different on each board. The boards are used as Rx during the measurements and can be seen in figure 8, 9, 10, and 11. The Tx can be seen in figure 12. From the theoretical part of this report, it is known that the size, number of turns, and shape of the antenna will affect the amount of received power.

4.1.1 Information about board Y1

Board Y1, which is depicted in figure 8, is used to send out pulses to electrodes that are connected to a nerve. It contains the harvester chip ST25DV04K-IER6S3 [32] from ST microelectronics and a DC/DC converter that is used to smooth out switching noise into regulated DC voltages. It is implemented on an FR4 (FR4 is is a composite material composed of woven fiberglass cloth with an epoxy resin binder that is flame resistant) board with a planar antenna which is gold plated, the coil has seven turns, and the measurement on the outer coil is $23 \cdot 34 \ mm^2$.
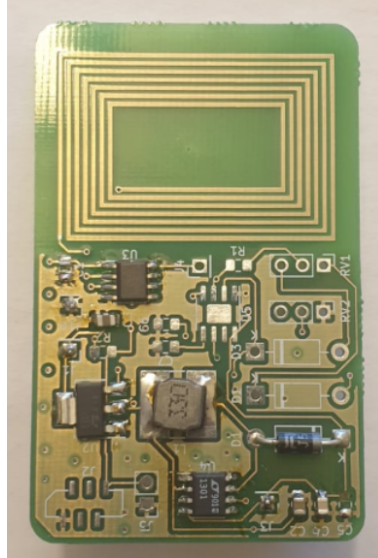
Figure 8: Picture of board Y1 where the antenna is gold plated. The coil has seven turns and the measurement on the outer coil is $23 \cdot 34 \ [mm^2]$.

4.1.2 Information about board Y2

Board Y2, which is depicted in figure 9, is used to send out pulses to electrodes that are connected to a nerve. It contains the Harvester chip ST25DV04K-IER6S3 [32] from ST microelectronics and a DC/DC converter that is used to smooth out switching noise into regulated DC voltages. It is implemented on an FR4 board with a planar antenna which is gold plated, the coil has nine turns, and the measurement on the outer coil is $50 \cdot 50$ mm^2.
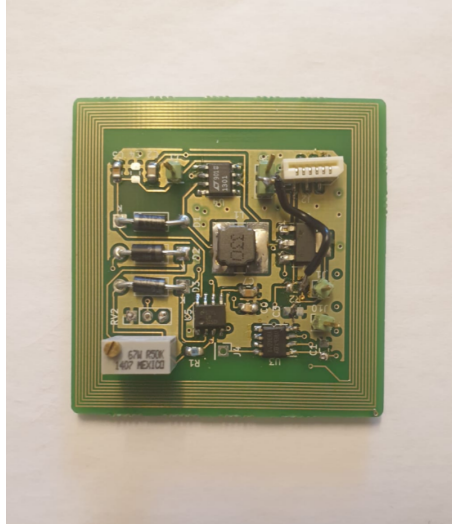
Figure 9: Picture of board Y2 where the antenna is gold plated. The coil has nine turns and the measurement on the outer coil is $50 \cdot 50$ $[mm^2]$

4.1.3 Information about the red board

The red board can be seen in figure 10. It is an NFC RFID tag that is offering 4 kbit of electrically erasable programmable memory [32]. It contains a Harvester chip ST25DV04K from ST microelectronics and an AC/DC converter [32] which takes the AC power and converts it to unregulated DC power. It is implemented on a board with unknown material with a planar antenna where the material is unknown, the coil has nine turns, and the measurement on the outer coil is $14 \cdot 14$ mm^2.

Figure 10: Picture of the red board where the material of the antenna is unknown. The coil has nine turns and the measurement on the outer coil is $14 \cdot 14$ $[mm^2]$.

4.1.4 Information about the Ams board

The Ams board can be seen in figure 11. It is an ISO15693-compliant tag for use with NFC and HF RFID [33]. It contains the harvester chip SL13A-DK-ST-QFN16 and and an AC/DC converter [34] which takes the AC power and converts it to unregulated DC power. It is implemented on a board with unknown material with a planar antenna where the material is unknown. The coil has four turns and the measurement on the outer coil is $41 * 71\ mm^2$.

Figure 11: Picture of the Ams board, the material on the antenna is unknown. The coil has four turns and the measurement on the outer coil is $41 * 71\ [mm^2]$.

4.1.5 Information about the transmitter board

The transmitter board, as depicted in figure 12, is an integrated transceiver module for contactless communication at 13.56 MHz [35]. The board has an integrated RF level detector [35] and can therefore be used as an Tx. The board has an operating power supply range from $2.7 - 5.5$ V [35]. The material of the antenna is unknown and the coil has three turns and the measurement on the outer coil is $46 * 60\ mm^2$. The inductance for the board is given in the data sheet as $1.91 * 10^{-6}$ H [36].
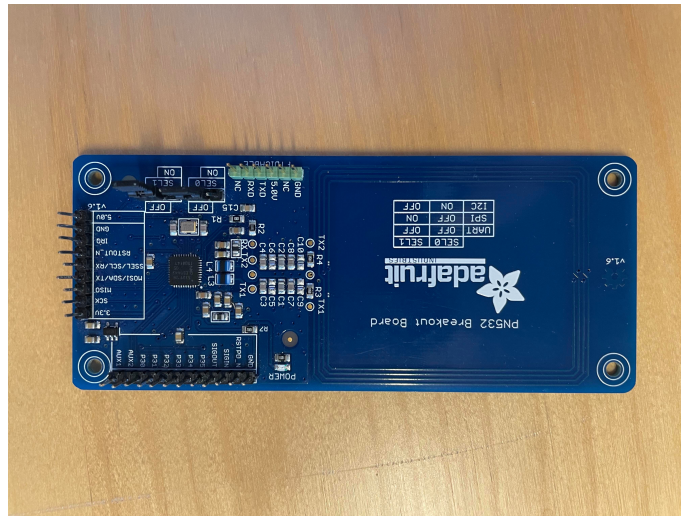
Figure 12: Picture of the transmitter board, the material of the antenna is unknown. The coil has three turns and the measurement on the outer coil is $46 * 60\ [mm^2]$.

5 Method

The project exists of two main parts. The first part is an evaluation of the previous work, the evaluation includes building a test bench and test different boards provided by the ISY department at Linköping University. The second part is the development of a voltage control feature that should coexist with the previous work. The voltage control development consists of two parts, the first one contains a physical setup with an Arduino, breadboard with LEDs, and a function generator that is programmed in Python. The second part aims to convert the first part into a circuit design, that later shall be added to the existing boards.

5.1 Evaluation of previous work

The boards have different antennas that shall be evaluated to see which board that have the best efficiency. There will be different test setups to determine the best suited antenna for nerve stimulation. This is done both with theoretical calculations and with practical tests. The Rx antennas are connected to an EH where the output is measured from, and compared for the different antennas to see which antenna has the best efficiency.

The Y1, Y2, and the red board have the same type of EH. The Y1 and Y2 board does not have a data sheet. In the data sheet for the red board the expected value from the EH cannot be found [32]. The Ams board has another type of EH, the expected output from that one can be found in the Ams data sheet [33]. The output voltage from the boards EH were measured by placing the boards on the Tx. The output is measured with a multi-meter. The output values only differ at the second decimal therefore are the values from the Ams data sheet assumed as parameter for the EH calculations on the other boards.

5.1.1 Theoretical evaluation

The efficiency of the four boards is calculated. The coupling factor (K) is the power transfer efficiency between the Tx and Rx. To calculate the value of $K = \eta_1$ is the inductance for Rx and Tx needed. The inductance is calculated with help of a website where the parameters of the antenna is inserted [37]. The parameters needed for the calculation are the height, width, number of turns, the coils diameter and the relative permeability. The output voltage on the boards are measured with a vernier caliper.

The antenna materials could not be found in the data sheet for the Ams and the red board. The Y1 and Y2 boards were built by the supervisor Yonatan Kifle and information about the antenna material could therefore be provided.

The antennas on the Y1 and Y2 board consist of gold. Gold was then used as a parameter for all the boards in the calculations. The relative permeability for gold is found in Physics handbook [24]. The inductance for the Tx where given in the boards data sheet as $1.91 * 10^{-6}$ H [36]. The measured parameters for the different boards can be found in the result section, in table 2. Efficiency through the EH will be $\eta_2 = 0.945$, which can be found in the data sheet [34]. The output efficiency for a board can be calculated as

$$\frac{P_r}{P_t} = \eta_1 \cdot \eta_2 = K(z) \cdot \eta_2. \tag{5}$$

To compute graphs for P_{in}/P_{out} the equation is inserted into MATLAB, where the value of the coupling factor depends on the distance. The efficiency between $0 - 10$ cm is then plotted and saved. The MATLAB code can be seen in appendix H.

To have a constant current in the Rx the power from the sender needs to be regulated when the distance z is changed. The power from Rx can be calculated by the power expression $P = I^2 R$ and then be derived into equation 4, the following expression is obtained,

$$\frac{P_{out}(z)}{P_{in}(z)} = \frac{R_r \cdot I_{const}^2}{P_{in}(z)} = K(z) \cdot \eta_2. \tag{6}$$

Where R_r is the resistance in the Rx board that were measured with a multi-meter. P_{in} is derived from equation 6 and can be written as

$$P_{in}(z) = \frac{R_r \cdot I_{const}^2}{K(z) \cdot \eta_2}.$$ (7)

In order to simulate a value of $P_{in}(z)$, the Y1 and Tx were used where $I_{const} = $ mA. The calculations for $P_{in}(z)$ are done in MATLAB and the code can be seen in appendix I. The plots from the theoretical calculations can be seen in the result section.

5.1.2 Practical evaluation

From the theoretical section it is known that the distance will affect the mutual inductance 2. The goal of the test bench is to measure the output voltage for different distances between the Rx and the Tx board. The selected output from the Rx should be collected at the test points and written to a *.Txt* file.

A step motor were bought to regulate the distance between Rx and Tx with precision. The step motor consists of metal and to prevent the metal from affecting the magnetic flux, a clip were used to place the board at a distance from the motor. The plastic clip was attached to the motor to put the test board 7 cm away from the metal.

The output was measured after the EH on all the boards. The Y1 and Y2 board can be seen in Figure 8 and Figure 9 respectively and are measured between pin J1 and J10 (ground). The red board can be seen in Figure 10 and is measured between pin EH and GND. The Ams board can be seen in Figure 11 and is measured between pin VSC and VEXT. The Tx for this evaluation is an integrated transceiver module and can be seen in Figure 12.

5.1.3 Test setup

The testing is a complement to the theoretical calculation of the boards efficiency. There will be 100 runs for each setup and board. Five different tests were executed on each board, the different tests are listed below.

- Having the Rx and Tx parallel, see Figure 13.
- Test with a 45° angle between Rx and Tx, see Figure 15.
- Test with skin imitation on the Tx, see Figure 18.
- Test with a pork chop on the Tx, see Figure 17.
- Set the Rx and Tx side by side, see Figure 16.

In Figure 13 the parallel setup can be seen. The Tx is fixed on the plank and the Rx will be placed in the clip. The clip is fixed to the step motor. This is the best scenario for when the power transfer could occur. This test will be the model for the rest of the tests and a reference setup.
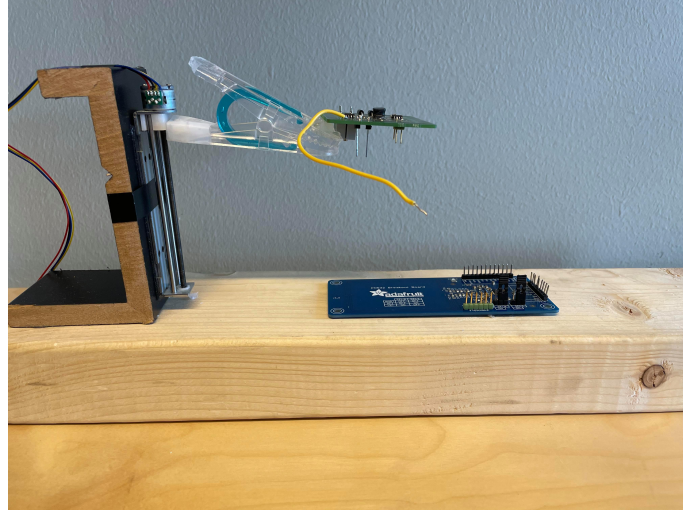
Figure 13: Test bench for the tests with the parallel setup, the Rx are placed in the plastic clip. Rx is Y1 board in this Figure

The first and third test setup are all done by placing the Rx in the clip and possible skin imitation on the Tx. To make the test at an $45°$ angel is the test bench is modified which can be seen in Figure 15. The solution for this were to design an arm that can be connected to the clip in the test bench. The arm can be seen in Figure 14. The arm is designed in Auto desk fusion and then 3D-printed, the design can be seen in appendix B.
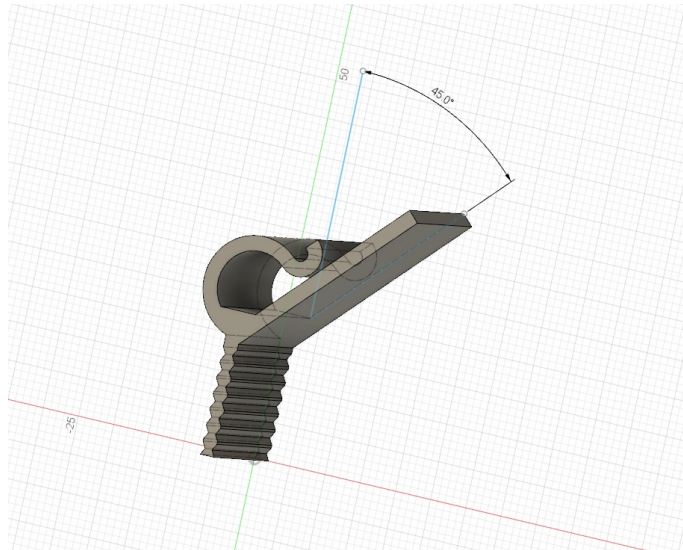
Figure 14: Design of arm. The clip on the arm can hold Rx at an $45°$ angle relative to the Tx in the test bench.

The arm has a clip on it where the Rx can be placed at an 45° angle. The Rx will be a little bit further away from the step motor to compensate for this. The Tx is moved to align with the Rx. The test aims to cover the case where the Rx is not held parallel to the Tx. In Figure 15 can the test bench with the arm connected to the clip be seen.
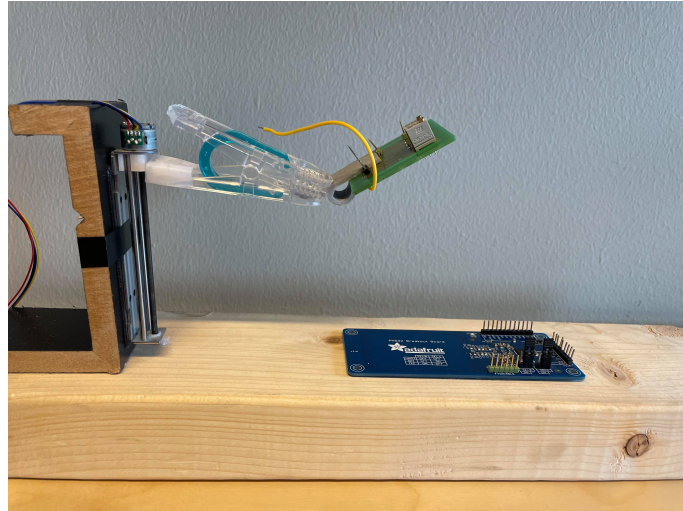
Figure 15: Test bench for the setup measuring at $45°$, the Rx is placed in the arm. Rx is Y1 board in this Figure

In Figure 16 the setup for the side by side tests can be seen. For future reference, it is relevant to investigate the behavior when the Rx and the Tx are not overlapping at all.
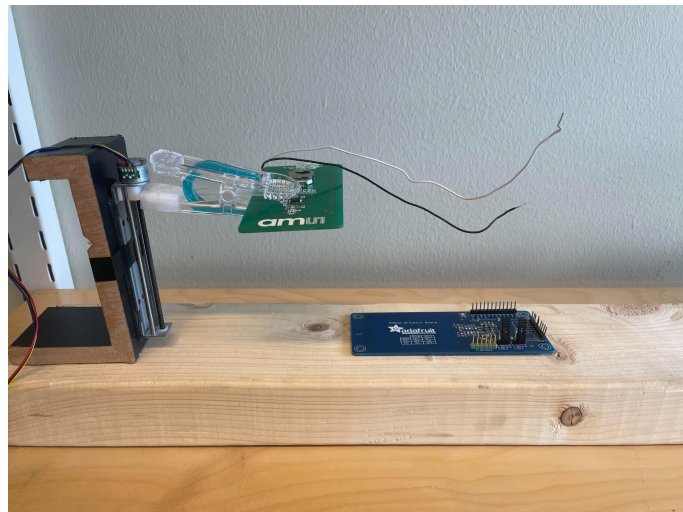
Figure 16: Test bench for the tests with the side by side setup, the Rx is placed in the plastic clip. Rx is Ams board in this Figure

In Figure 17 the setup can be seen for the tests with the pork chop. The pork chop was not put on the Rx due to the step motors incapacity to move such heavy weight. For future reference it is relevant to investigate the behavior when the Rx is a bit under the skin, this is mimicked with a pork chop.
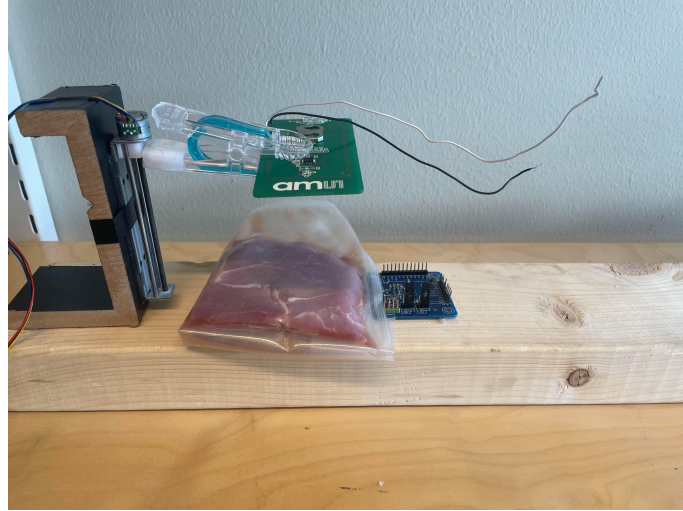
Figure 17: Test bench for the tests with pork chop setup, the Rx are placed in the plastic clip. Rx is Ams board in this Figure

In Figure 18 the setup for the skin imitation tests can be seen. For convenience, the skin imitation is put on the Tx instead of the Rx. For future reference it is relevant to investigate the behavior when the Rx is just under the skin, this was mimicked by a skin imitation fabric.
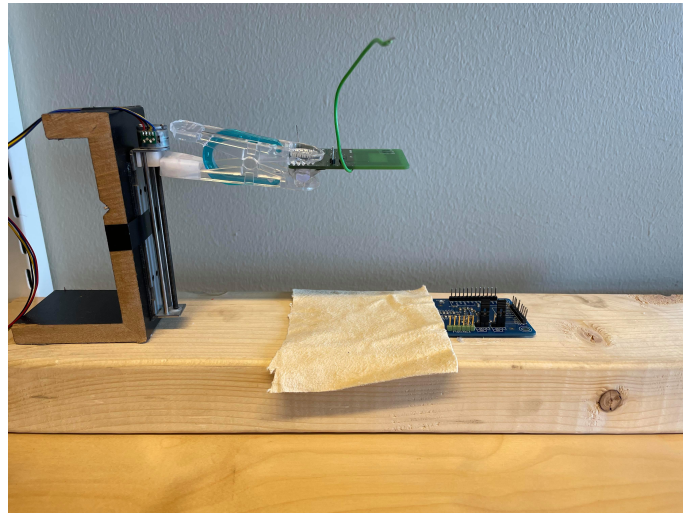
Figure 18: Test bench for the tests with the skin imitation setup, the Rx is placed in the plastic clip. Rx is Y1 board in this Figure

The step motor is driven by an Arduino that is connected to an Arduino complement called Arduino motor shield. The motor shield is necessary due to that it contains a motor controller that is connected to the step motor in order for it to run properly [38]. The Arduino code is written in C.

The step motor slider length is divided into 360 steps. One step moves the clip 0.25 mm. Figure 13 illustrates the step motor, if the step is a positive value it moves the step motor upwards, and downwards if the step is negative.

The Arduino will move the motor if the step value is inserted in a function called

```
myStepper.step(stepp),
```

the function is located in

```
<Stepper.h>
```

libary. [39]

When the step motor starts there is no indication of where the step motor is located on the slider. The step motor needs to be at the top of the slider, therefore before starting a test the step motor needs to be moved to the top. There is a 9 V battery connected to the Arduino board to give the step motor extra power.

The code is implemented assuming that the user enters the amount of test points and the amount of tests that should be executed. The Arduino code is implemented in a while loop to make the motor stop after the last test. The step motor can move along the slider, which sets the board range from $0 - 8.5$ cm (can be shorter depending on the design of the board). The output voltage in the Rx is measured from the input at the analog port on the Arduino. The analog inputs on the Arduino can take in 5 V. The analog in-port generates a step value that consists of $0 - 1023$ steps and the input voltage has an accuracy of 0.0049 V. To translate the input voltage from steps to a voltage the following expression is used [40]

```
voltage=step*5/1023.
```

The value of the voltage at the test points is sent to the COM-port. The step motor then drives 1 cm and saves the measured voltage value and then drives again. This is repeated for all the test points, when finished the motor will move back up to the start position and is repeated 100 times. The Arduino code for the test bench can be seen in the appendix A.

The values that are sent to the COM-port are saveed to a *.Txt* file. This is done with a program called cool term [41]. If cool term is connected to the COM-port it will load the values and print them to a text file.

MATLAB was used to display the data from the tests in graphs. The text file that is created from cool term is loaded into MATLAB as an array. The array is rearranged to be a matrix with dimension $100 \cdot testpoints$. The mean value of the test points and the confidence interval is calculated and plotted. The MATLAB code for the boards can be seen in appendix C - F.

The Tx is connected to a laptop using a USB connection. The Tx is programmed in Python and the program used is Spyder provided by Anaconda. The code can be seen in appendix L. For the code to work the $adafruit_{pn532}$ library needs to be added in the file path. This module allows communication with a PN532 RFID/NFC shield or breakout board using I2C, SPI or UART. The Tx is activated to send out the power specified in its data sheet which is 500 mW. The program does indicate if an RFID/NFC card ID is detected and writes out the ID to the console.

5.2 Voltage control development

One of the aims of the project is to create a voltage regulator to make sure that the amount of current never exceeds a level that can be harmful to a nerve. An overview of this new functionality can be seen in Figure 19. The voltage that is sent into a nerve will go into the Arduino analog input in this setup. The Arduino will transfer a signal that gives information about the voltage level. The computer takes this signal and will regulate the power and then update the function generator for it to be sent out to the Tx.
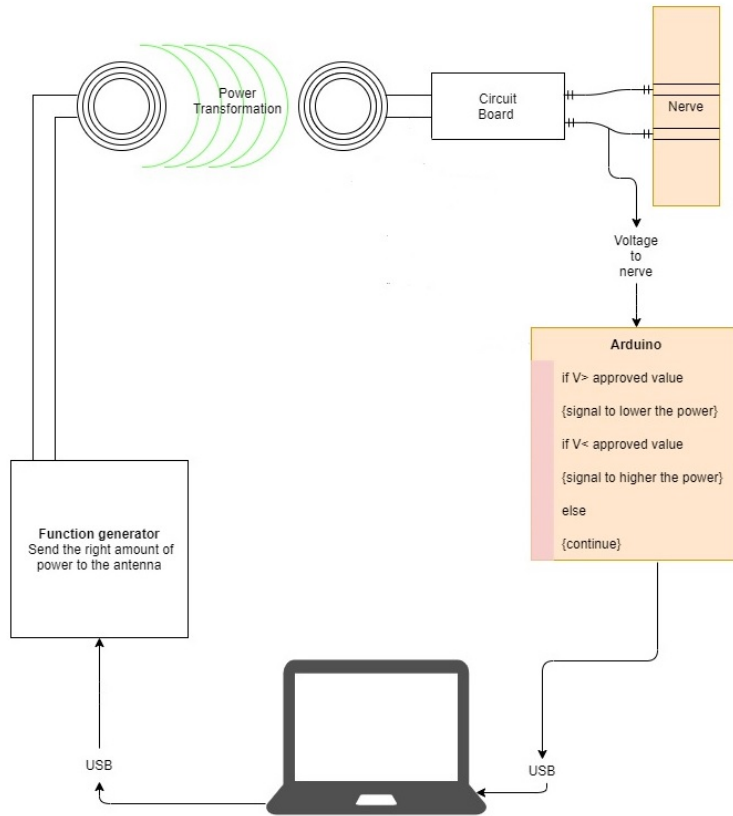
Figure 19: The Rx will activate when PTx is received. The output from the Rx goes into the Arduino, the Arduino categories the voltage as low, approved, and high. The voltage categorizes is sent into the computer that regulates the function generator. If the received voltage is too high or low the computer will regulate the function generator, until the Rx is within the approved level.

5.2.1 Arduino and function generator

A solution to the uncontrolled voltage that is sent out from the boards needed to be found. To implement this solution a function generator and an Arduino were used. The idea is that when the Rx is receiving a voltage that is too high for a nerve, the function generator will regulate the output from the transmitter antenna. When implementing this functionality an Arduino UNO is used together with the function generator. The Arduino UNO and function generator are programmed in Python. Anaconda3 and Spyder were used to set up an environment to work in. The package that is used in python in order to get the Arduino to work is called pyfirmata. To get this going on the Arduino it needs to be uploaded to the Arduino through the Arduino IDE program. When the USB is connected make sure in the tab marked *Tools* that the right board and port is selected [42]. To program the Arduino choose the tab *File –> Examples –> Firmata –> StandardFirmata*, which opens an example file. The last step is to press upload under the tool bar, then it is done the Arduino can be used in python [42].

The Arduino analog inputs can take in 5 V, but in python the value read from the Arduino is between 0 V and 1 V which needed to be regulated for. The Arduino and the function generator are connected to the computer through the USB ports. A setup for the function generator is done to have reasonable start values. The input

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from the Arduino is read and then sent into an if-statement. The if-statement has three conditions where the first statement tests if the received voltage is less or equal to one. If the statement is true a yellow led will be lit and the amplitude in the function generator will be changed with a set step length, which is 0.25 in this case. The second condition checks if the input voltage is greater than 3 V, when this is true a red led will be lit and the amplitude in the function generator will be changed with the same step size as in the first condition. When the voltage does not match either the first or second condition there is a third condition where all these cases will enter. Here a green LED will be lit but nothing else will be done due to that the voltage is within the approved interval. The setup can partly be seen in Figure 20 (the function generator is not in the picture) and the code can be seen in appendix K.

The solution with the LEDs will then be translated into a circuit with transistors in order to not destroy the LEDs.
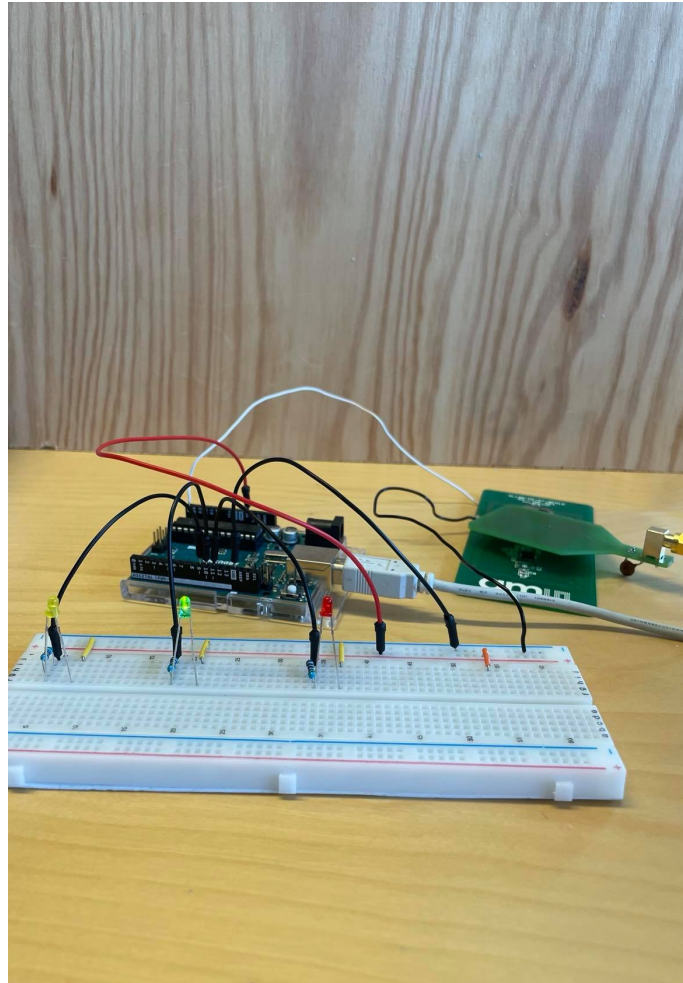
Figure 20: Test bench for the physical voltage control development, The function generator is missing in the Figure.

5.2.2 Circuit design

To convert the functionality from physical LEDs, a limiter circuit was used. The limiter showed in Figure 7 can be modified as can be seen in Figure 21, this Figure was made by Samir G. Sabah [11].
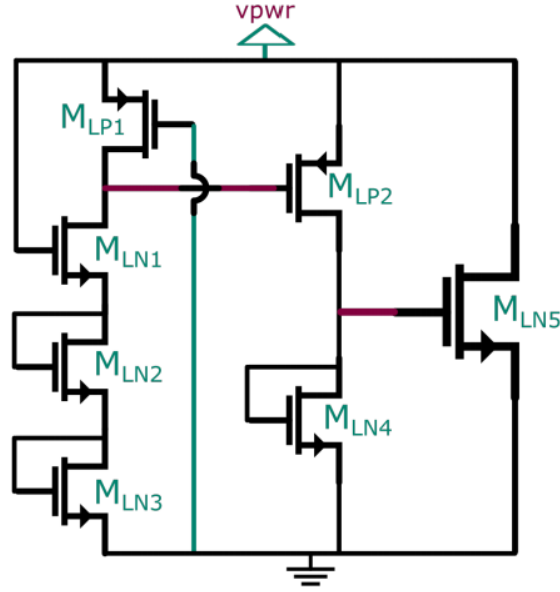
Figure 21: The redrawn limiter [11]. It contains two PMOS transistors and five NMOS transistors. There is a single input voltage that feeds the whole circuit. Depending on the input voltage level different transistors are turned on at different times. The transistors named M_{LN2} and M_{LN3} act as diodes and are turned on if the input voltage is larger than some threshold value.

Figure 21 is modified in the sens that it is not grounded at the bottom. The reason for this is that it should not only limit a circuit, the constant value generated from it shall be used as an output. The circuit will give a constant current/voltage and the output value in simulations is obtained from the drain of M_{LN5}. When $vpwr$ is higher than a threshold value ($Vthn$) the transistor M_{LN1} is turned on and current can flow through, which means that the output at M_{LN5} gets limited. M_{LN2} and M_{LN3} act as diodes and are turned on when the voltage level is higher than a set threshold value. The threshold values can be modified by sizing the transistors. When sizing the transistors the length (L) was set to a constant value for all the transistors, which was slightly larger than the minimum value. The width (W) of the transistors were set individually and the values depended on the approved size of $vpwr$.

The modified circuit from Figure 21 is implemented and simulated in Cadence. The transistors that were used are from the *gpdk045* library, the transistors are named *nmos1v* and *pmos1v*. As input voltage, a ramp function was used, to increase the voltage slowly. When the voltage is increased slowly the moment and point where the current gets constant can be captured. The voltage source is ideal and therefore it is easier to verify the functionality of the circuit if the current is analyzed. When the current curve reassembles something constant the output voltage will be obtained if the ramp function is plotted in the same window.

6 Results

The results from the theoretical calculations and the practical tests are presented in this chapter, as well as the results from the voltage control development.

6.1 Theoretical calculations

The parameters that were used for the theoretical calculations on the boards are listed in table 2.

Board	Y2	Y1	Red	Ams
Number of turns on coil	9	7	9	4
Loop Height [mm]	50	23	14	41
Loop Width [mm]	50	34	14	71
Wire Diameter [mm]	0.5	0.5	0.25	0.25
Relative Permeability	0.999998	0.999998	0.999998	0.999998
Calculated inductance [H]	0.0000124	0.00000439	0.00000358	0.00000377

Table 2: Parameters for the Rx boards. The coil parameters in the table are: number of turns, height, width, wire diameter, relative permeability, and calculated inductance.

The amount of power that the transmitter needs to send out in to keep 1 mA in the Y1 board for different distances can be seen in figure 22. The resistance in the Y1 board was measured to 20 $M\Omega$.
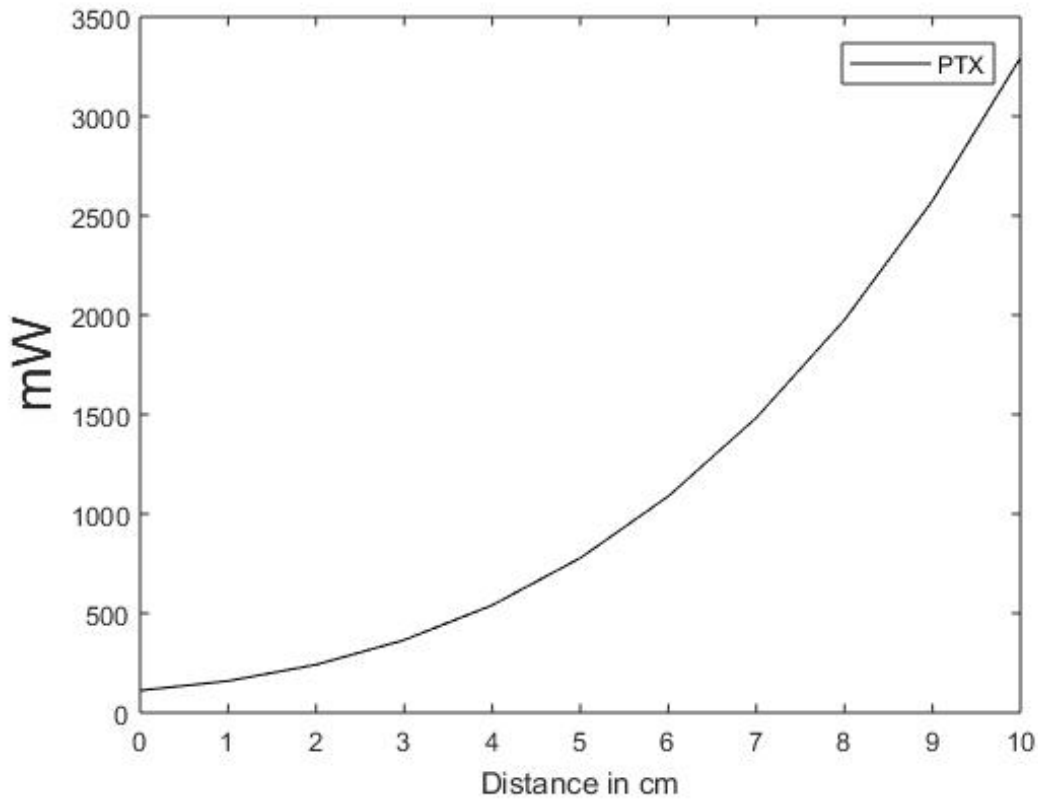
Figure 22: The graph shows the PTx output to keep constant current in the Rx. The plot shows the theoretical calculations with the red board as Rx and the Tx

Efficiency for all the boards over different distances can be seen in figure 23.
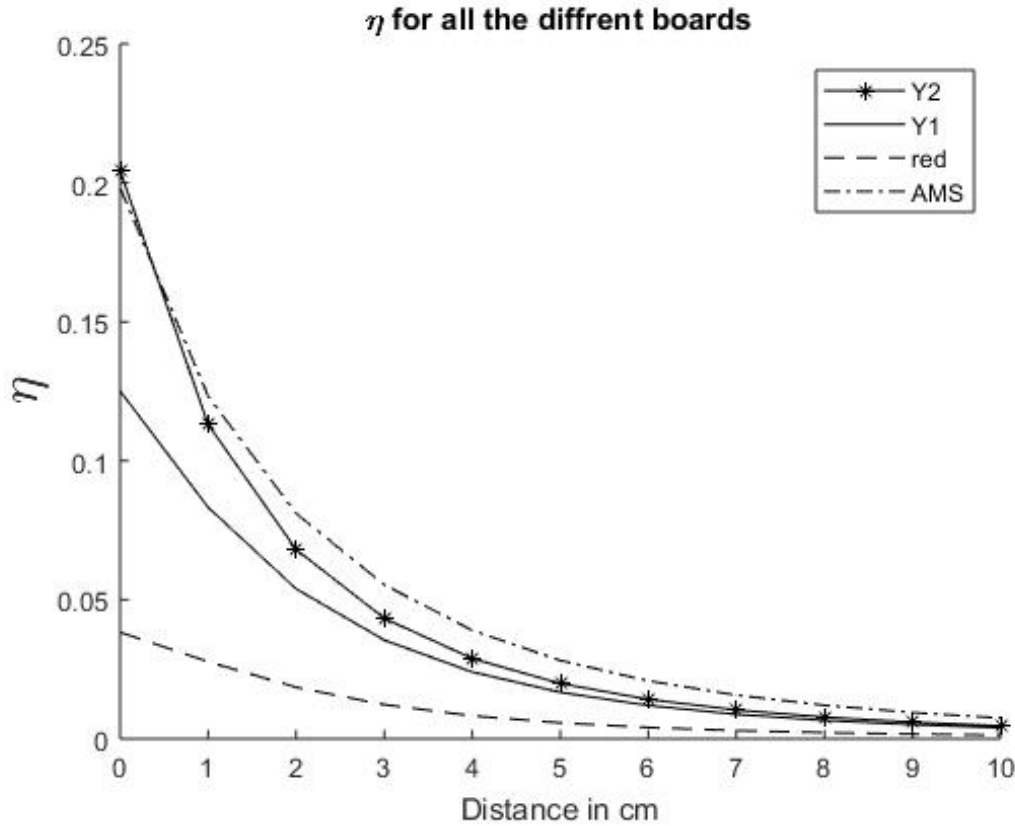
Figure 23: The calculated efficiency for the Y2, Y1, red, and Ams board. The efficiency decreases exponentially when the distance increases.

6.2 Result from the voltage control development

In the following section results from the different voltage control solutions are presented. The results from the setup with the LEDs are presented with a series of pictures. The results from the circuit design are presented by figures containing the circuit design and simulations.

6.2.1 Arduino and function generator

The result from the voltage control implementation when the Arduino, function generator and a bread board with LEDs was used can be seen in figure 24. From the start, the voltage from the function generator is set to 5 V. This is outside the approved range which will turn on the red LED, see picture *a* in figure 24. When the code has been running for a few seconds the green LED turns on which means that the voltage has been regulated and is now within the approved interval, see picture *b* in figure 24. In picture *c* in figure 24 the Tx has been moved further from the Rx which makes the yellow LED turn on and indicates that the voltage is to low. After a few seconds, the voltage has been regulated and the green LED turns on. See picture *d* in figure 24. Then the Tx was moved to the Rx and the red LED turns on, see picture *e* in figure 24. The Python code can be seen in appendix K.
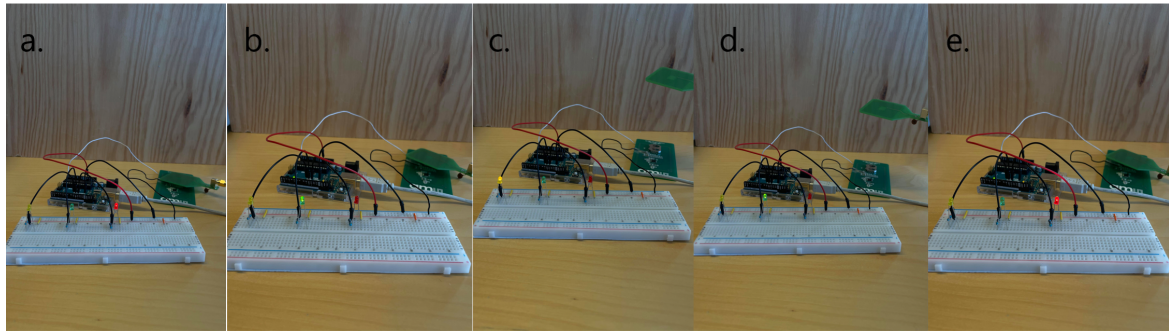
Figure 24: Series of pictures of how the LEDs shift depending on how the Tx moves relatively the Rx

6.2.2 Circuit design

The modified limiter circuit can be seen in figure 25. The harvested energy is the input voltage (V_{EH}) in the circuit. Here the bulk of the PMOS is connected to the harvested energy, because V_{EH} is equal to V_{DD} in this case. The circuit consists of two PMOS transistors and five NMOS transistors. The first stage of the circuit marked with a yellow rectangle includes one PMOS transistor and three NMOS transistors, the PMOS is on when there is a high potential at V_{EH}. The two NMOS transistors called NM4 and NM5 in figure 25 act as diodes, they are turned on one at a time when the input voltage is higher than the threshold value. The NMOS transistors that act as diodes are used to provide the required voltage at the gate of the PMOS at the top of the rectangle and the rightmost NMOS, named NM6 in figure 25. The NMOS in the pink rectangle named NM1 act as a diode as well.
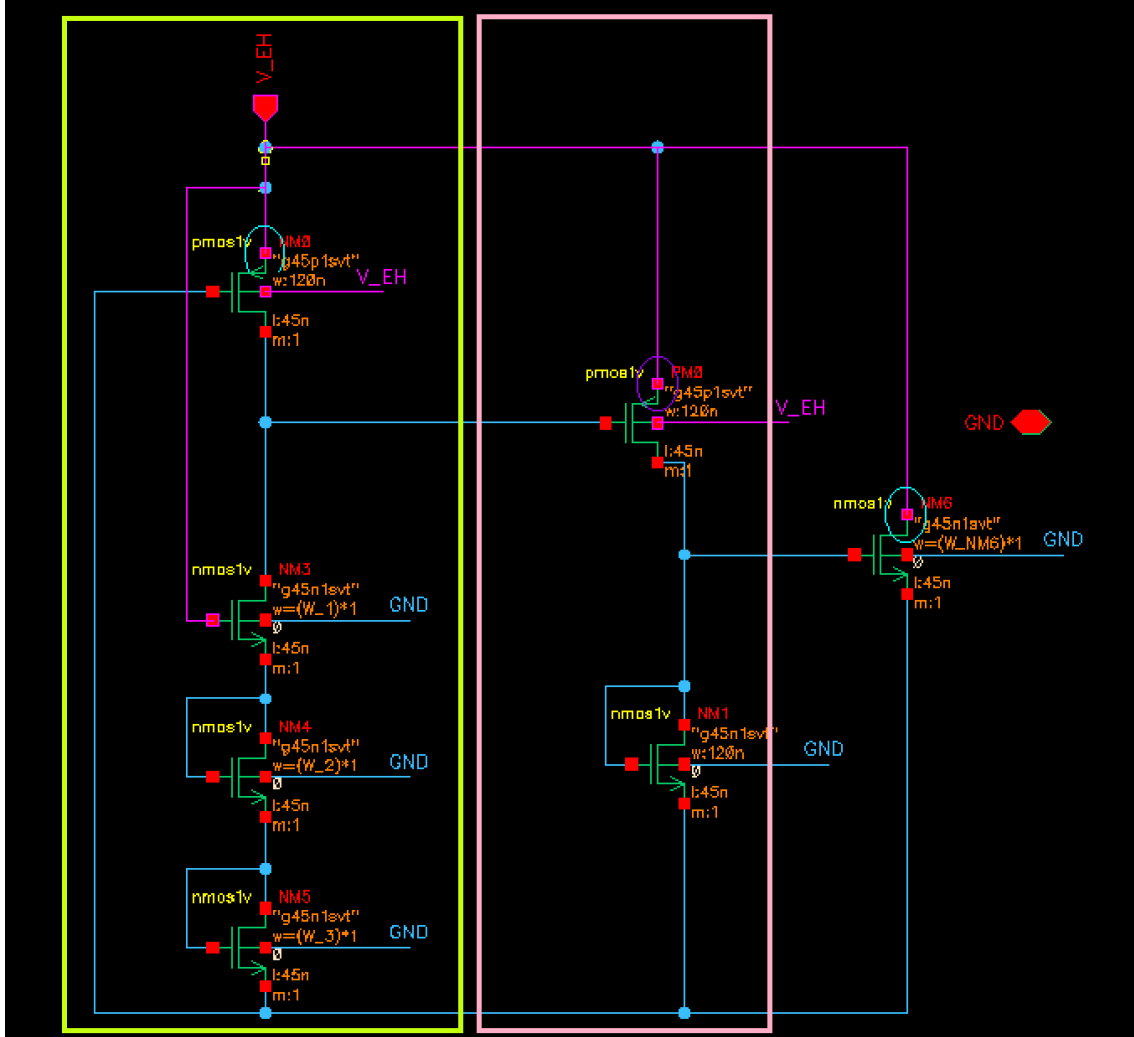
Figure 25: The modified limiter circuit implemented in Cadence.

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The results from the first simulation in cadence can be seen in figure 26. When the current become constant (yellow curve) the cross over between the two curves indicates what output voltage the circuit will give when a ramp function (red curve) is used. The input voltage V_{EH} was set to 3 V and the transistor settings can be seen in table 3. It can be seen that the output voltage is 1.8 V when $V_{EH} = 3$ V. It is verified due to the constant current in the drain node of M_{LN5}.
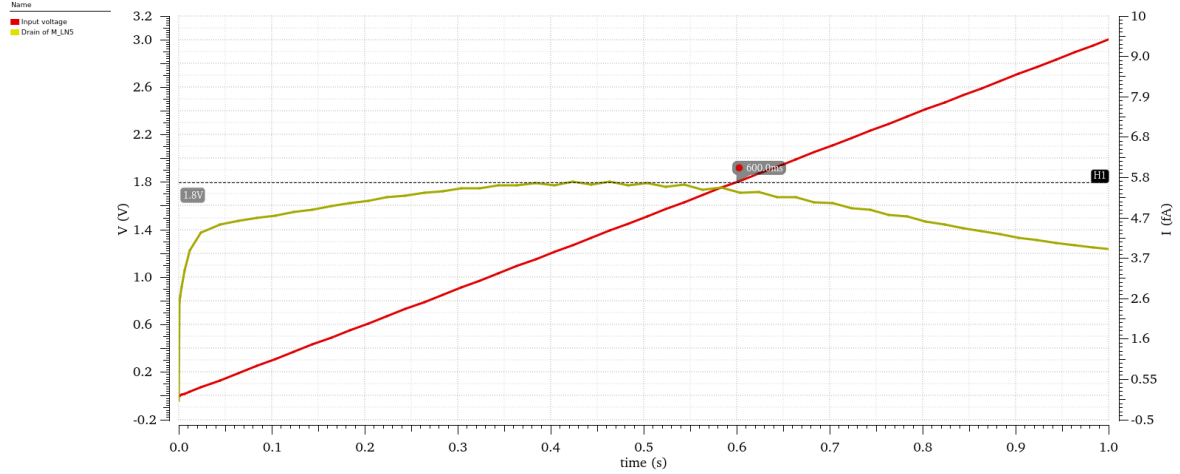
Figure 26: Simulation result from Cadence. The input voltage $V_{EH} = 3$ V. The voltage where the current gets constant is 1.8 V. The green/yellow curve is the current at the drain node for transistor M_{LN5} and the red curve is the input voltage.

The results from the second simulation in cadence can be seen in figure 27. The input voltage V_{EH} was set to 4 V and the transistor settings can be seen in table 3. It can be seen that the output voltage is 2.5 V when $V_{EH} = 4$ V. It is verified because the current is constant in the drain node of M_{LN5}.
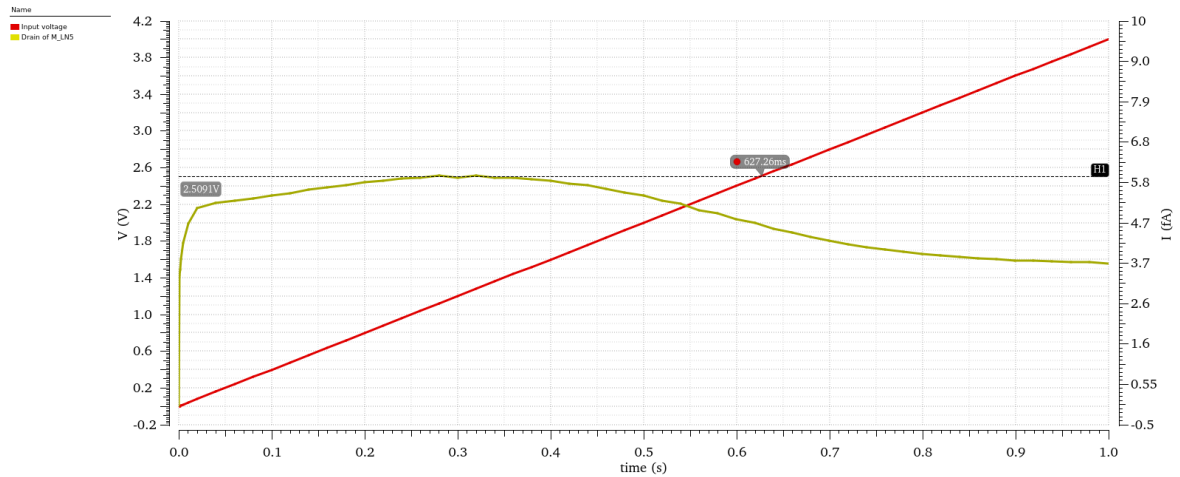
Figure 27: Simulation result from Cadence. The input voltage $V_{EH} = 4$ V. The voltage where the current gets constant is 2.5 V. The green/yellow curve is the current at the drain node for transistor M_{LN5} and the red curve is the input voltage.

The settings for the width of the transistors can be seen in table 3, the lengths were set to $50n$ m for all transistors.

Transistor	Width [nm]
M_{LP1}	120
M_{LN1}	120
M_{LN2}	120
M_{LN3}	120
M_{LP2}	240
M_{LN4}	120
M_{LN5}	600

Table 3: The width of the transistors in the modified limiter circuit.

6.3 Test results on individual boards

Here the test results from the physical test bench are presented and each subsection contains all tests for a certain type of board. The tests and their specifications can be seen in section 5.1.2. The distances vary between tests and boards, this is due to the setup.

Each graph will contain the confidence interval with a confidence level of 95 %, more about the confidence interval can be read in chapter 3.4. All graphs are made in MATLAB and the MATLAB code can be seen in appendix C-G.

6.3.1 Red board

The results from the test with the parallel setup for the red board can be seen in figure 28. The voltage is fairly constant from $0 - 4$ cm and from $4 - 8$ cm the voltage drops almost linearly. The confidence interval is larger around 0, 1, 3, 7 and 8 cm.
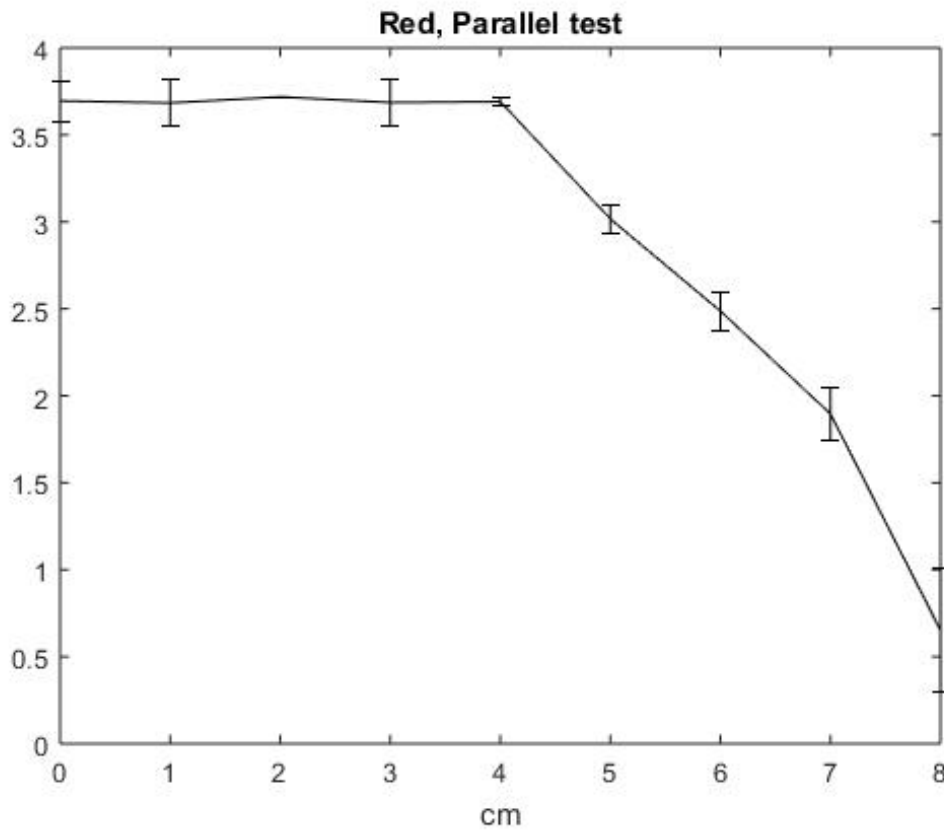
Figure 28: Measurements with the red board held parallel against the transmitter board. The voltage is fairly constant from $0 - 4$ cm and from $4 - 8$ cm the voltage drops almost linearly. The confidence interval is larger around 0, 1, 3, 7 and 8 cm

In Table 4 the average V_{in} for 100 runs on each centimeter can be seen.

$Distance$ [cm]	0	1	2	3	4	5	6	7	8
$V_{in,avg}$[V]	3.69	3.68	3.72	3.68	3.69	3.02	2.49	1.89	0.65

Table 4: Average input voltage $V_{in,avg}$ for each distance from the test with parallel setup for the red board

The result from the test with the angled setup for the red board can be seen in figure 29. From $0 - 3$ cm the voltage is relatively constant at 3.7 V. After 3 cm and up to 7 cm the curve decreases in a linear way. Between $7 - 8$ cm the curve flattens a bit and ends at 0.35 V. The confidence interval is larger at 1, 3, 7 and 8 cm.
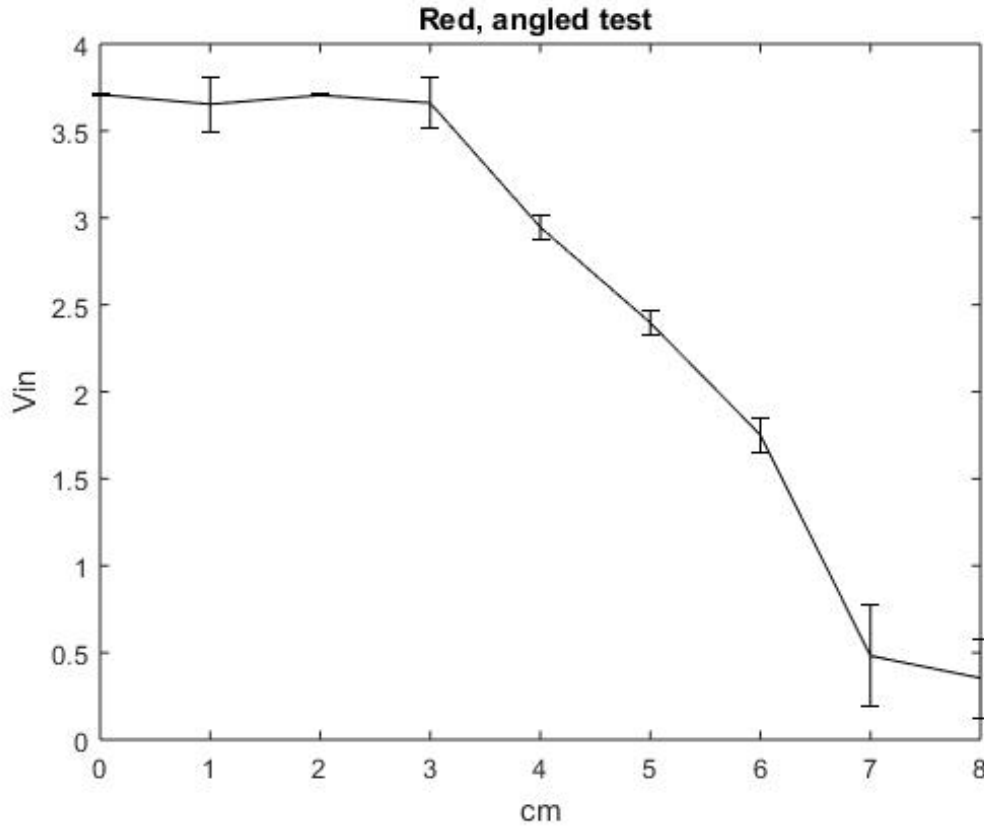
Figure 29: Measurements with the red board held with a $45°$ against the transmitter board. From $0 - 3$ cm the voltage is relatively constant at 3.7 V. After 3 cm and up to 7 cm the curve decreases in a linear way. Between $7 - 8$ cm the curve flattens a bit and ends at 0.35 V. The confidence interval is larger at 1, 3, 7 and 8 cm.

In Table 5 the average V_{in} for 100 runs on each centimeter can be seen.

$Distance$[cm]	0	1	2	3	4	5	6	7	8
$V_{in,avg}$[V]	3.71	3.65	3.70	3.66	2.94	2.40	1.75	0.48	0.35

Table 5: Average input voltage $V_{in,avg}$ for each distance from the test with angled setup for the red board

The results from the test for the skin imitation for the red board can be seen in figure 30. The first centimeters between $0-4$ has a fairly constant voltage around 3.7 V. Between $4-7$ cm the curve decreases in a linear way and after 7 cm the slope of the curve increases. The confidence interval is larger at 1, 3 and 8 cm.
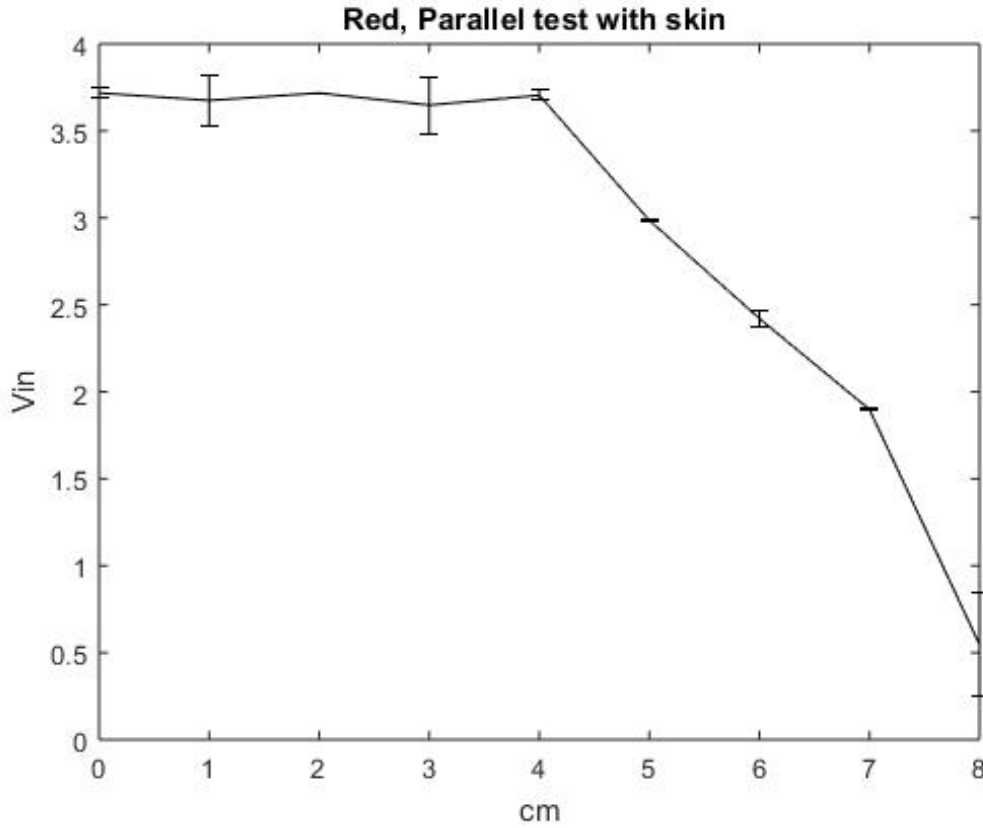
Figure 30: Measurements with the red board using skin imitation. The first centimeters between $0-4$ has a fairly constant voltage around 3.7 V. Between $4-7$ cm the curve decreases in a linear way and after 7 cm the slope of the curve increases. The confidence interval is larger at 1, 3 and 8 cm.

In Table 6 the average V_{in} for 100 runs on each centimeter can be seen.

$Distance$[cm]	0	1	2	3	4	5	6	7	8
$V_{in,avg}$[V]	3.72	3.67	3.71	3.65	3.70	2.98	2.42	1.90	0.55

Table 6: Average input voltage $V_{in,avg}$ for each distance from the test with skin imitation for the red board

The results from the test with the pork chop for the red board can be seen in figure 31. The measurement was made between $2-8$ cm due to the thickness of the pork chop. The curve is constant between $2-3$ cm with a voltage of 3.77 V. Between $3-8$ cm the curve can be approximated to be linearly decreasing and has an end voltage of 0.38 V. The confidence interval is larger at $7-8$ cm.
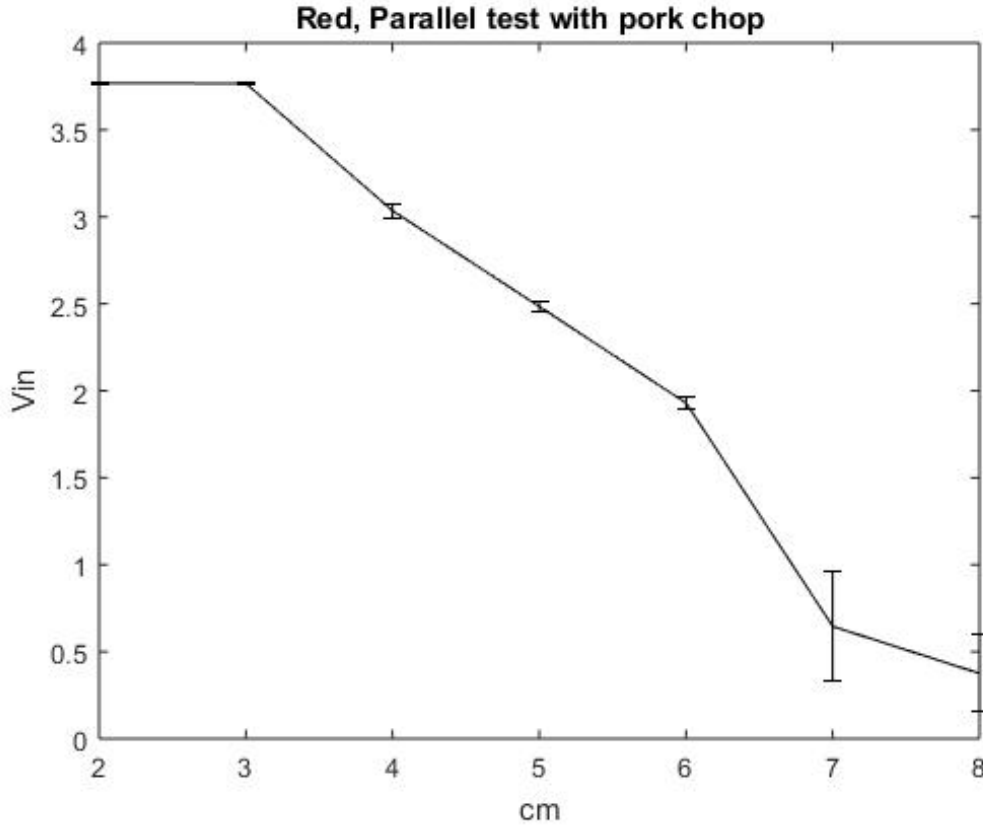
Figure 31: Measurements with the red board using a pork chop. The measurements starts at 2 cm. The curve is constant between $2-3$ cm with a voltage of 3.77 V. Between $3-8$ cm the curve can be approximated to be linearly decreasing and has an end voltage of 0.38 V. The confidence interval is larger at $7-8$ cm.

In Table 7 the average V_{in} for 100 runs on each centimeter can be seen.

$Distance$ [cm]	2	3	4	5	6	7	8
$V_{in,avg}$[V]	3.77	3.76	3.04	2.48	1.93	0.65	0.38

Table 7: Average input voltage $V_{in,avg}$ for each distance from the test with pork chop for the red board

The results from the test with the side by side setup for the red board can be seen in figure 32. From $1 - 2$ cm the curve is drastically decreasing from 3.19 V to 0.56 V. After 3 cm the curve gets fairly constant and has voltages around 0.2 V with a slight decrease after 6 cm. The confidence interval is larger at 2 cm. However, for all other distances than 1 cm the intervals are almost the same size.
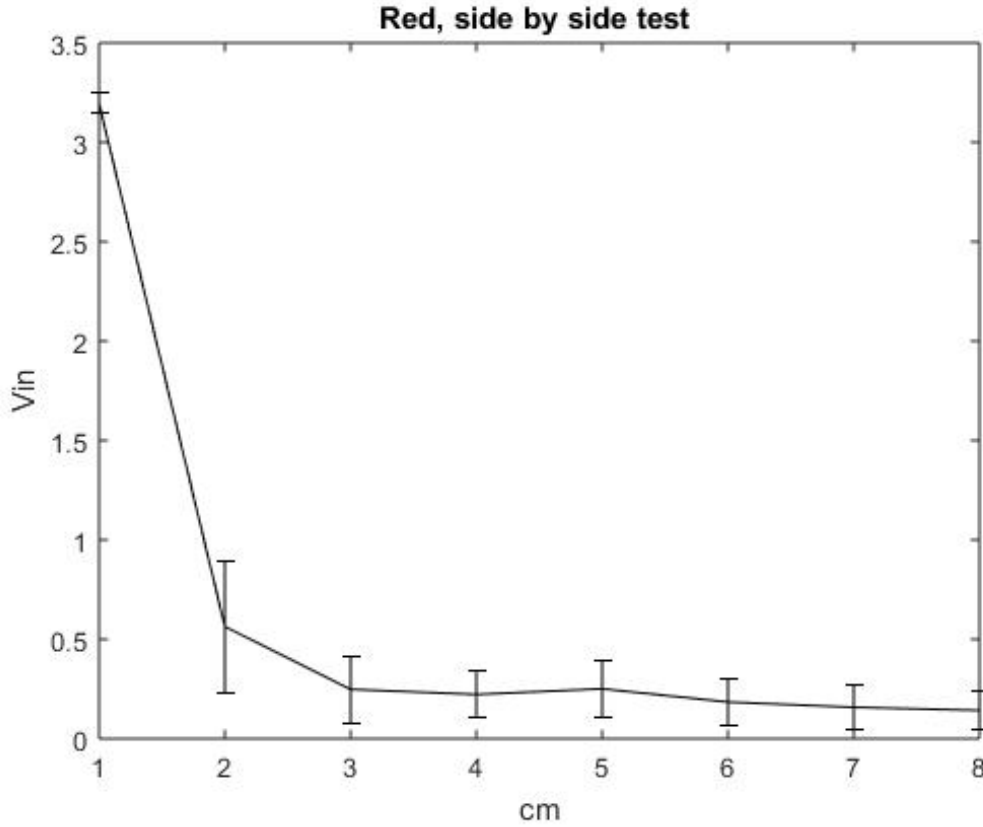
Figure 32: Measurements with the red board with the side by side setup. The first test was made at 1 cm. From $1 - 2$ cm the curve is drastically decreasing from 3.19 V to 0.56 V. After 3 cm the curve gets fairly constant and has voltages around 0.2 V with a slight decrease after 6 cm. The confidence interval is larger at 2 cm. However, for all other distances than 1 cm the intervals are almost the same size.

In Table 8 the average V_{in} for 100 runs on each centimeter can be seen.

$Distance$[cm]	1	2	3	4	5	6	7	8
$V_{in,avg}$[V]	3.19	0.56	0.25	0.22	0.25	0.18	0.16	0.14

Table 8: Average input voltage $V_{in,avg}$ for each distance from the test with the side by side setup for the red board

6.3.2 Y1

The results from the test with the parallel setup for board Y1 can be seen in figure 33. The curve decreases drastically between $0-3$ cm from 3.77 V to 0.75 V. From $3-8$ cm the curve is fairly constant. The confidence interval is low at 0 and 2 cm and almost the same for all the other distances.
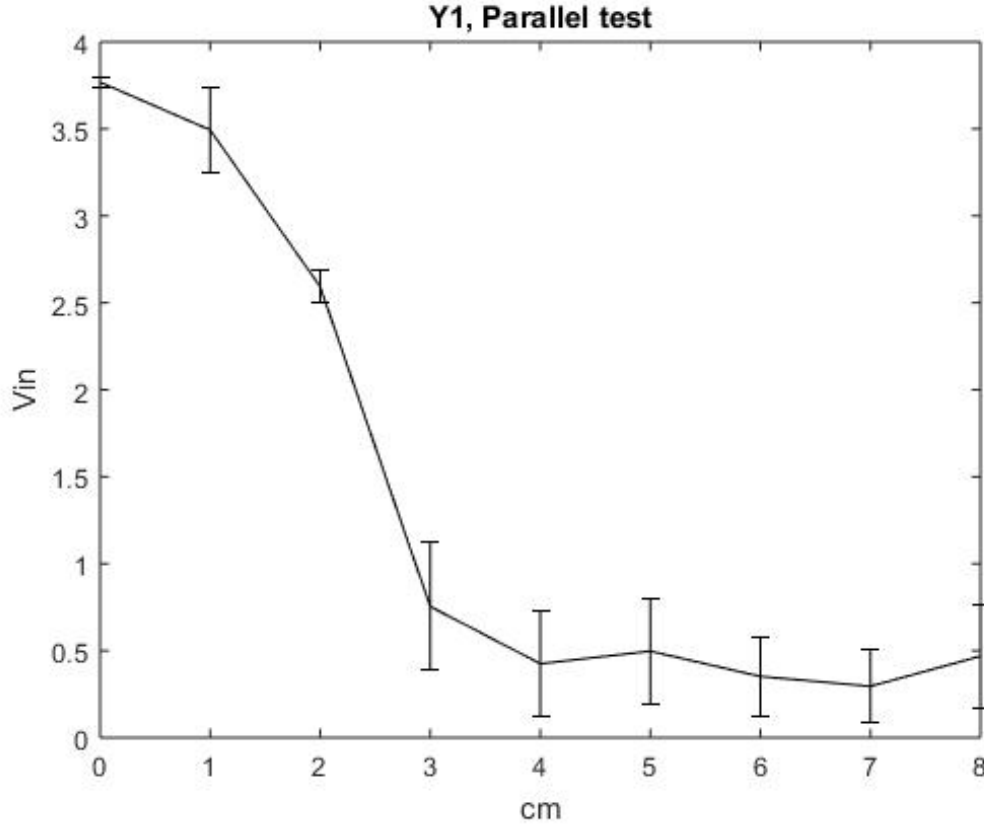
Figure 33: Measurements with the Y1 board with the parallel setup. The curve decreases drastically between $0-3$ cm from 3.77 V to 0.75 V. From $3-8$ cm the curve is fairly constant. The confidence interval is low at 0 and 2 cm and almost the same for all the other distances.

In Table 9 the average V_{in} for 100 runs on each centimeter can be seen.

$Distance$[cm]	0	1	2	3	4	5	6	7	8
$V_{in,avg}$[V]	3.77	3.49	2.59	0.75	0.43	0.5	0.35	0.30	0.47

Table 9: Average input voltage $V_{in,avg}$ for each distance from the test with parallel setup for the Y1 board

The result from the test with the angled setup for the Y1 board can be seen in figure 34. Between $0 - 3$ cm the curve is decreasing fast from 2.28 V to 0.37 V. From $3 - 8$ cm the curve is quite constant. The confidence interval is larger between $2 - 8$ cm.
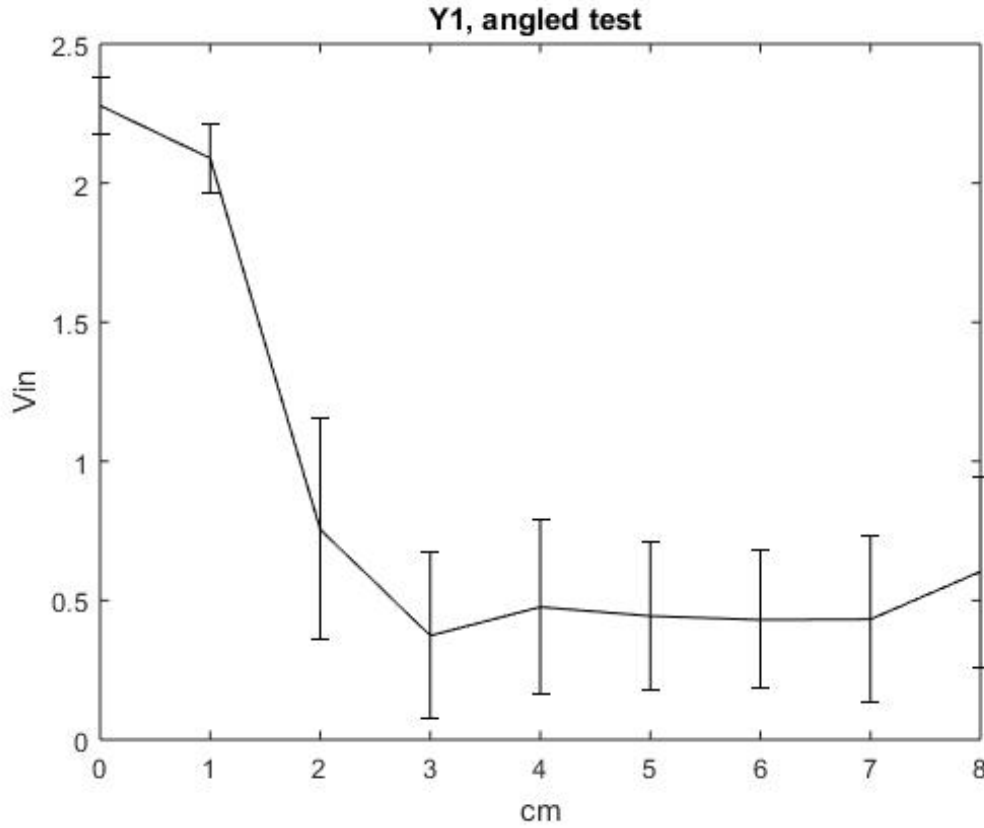
Figure 34: Measurement with the Y1 board with the 45° setup. Between $0 - 3$ cm the curve is decreasing fast from 2.28 V to 0.37 V. From $3 - 8$ cm the curve is quite constant. The confidence interval is larger between $2 - 8$ cm.

In Table 10 the average V_{in} for 100 runs on each centimeter can be seen.

$Distance$[cm]	0	1	2	3	4	5	6	7	8
$V_{in,avg}$[V]	2.28	2.09	0.75	0.37	0.48	0.44	0.43	0.43	0.60

Table 10: Average input voltage $V_{in,avg}$ for each distance from the test with the angled setup for the Y1 board

The results from the test with the skin imitation for the Y1 board can be seen in figure 35. Between $0 - 2$ cm the curve decreases fast from 3.59 V to 0.72 V. Between $2 - 5$ cm the curve decreases a bit more but only by 0.1 V each centimeter. After 5 cm the curve is relatively constant. The confidence interval is almost the same for distances between $2 - 8$ cm and relatively small for 0 and 1 cm.
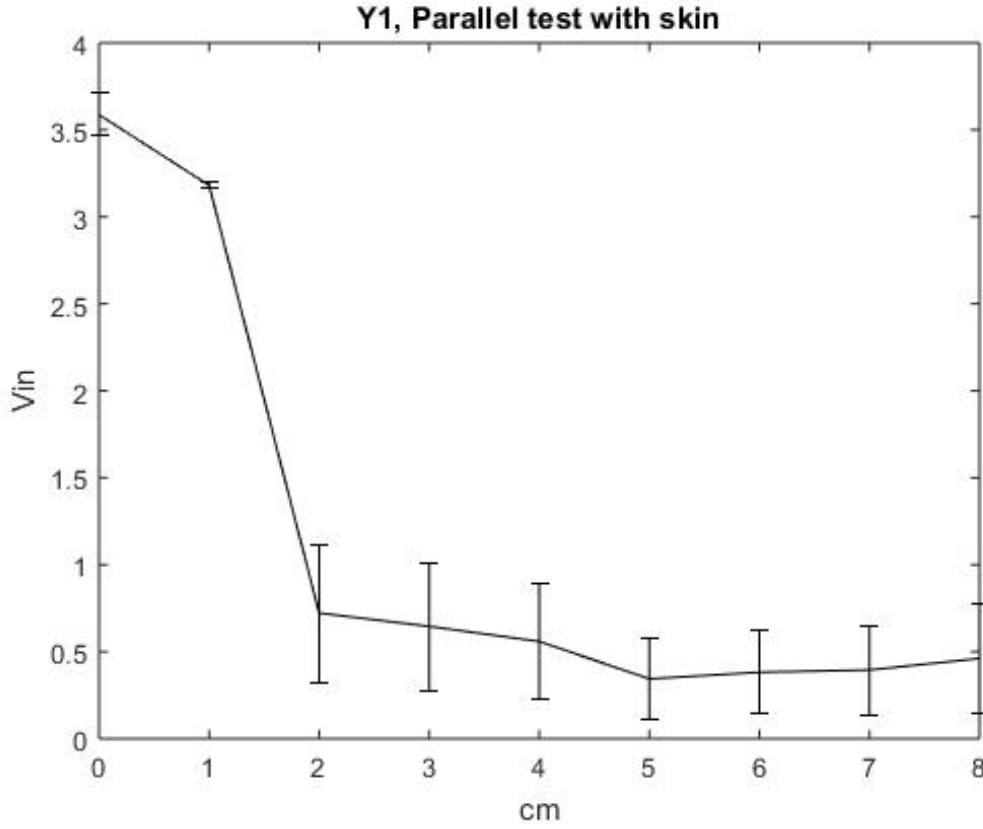
Figure 35: Measurements with the Y1 board with the skin imitation setup. Between $0-2$ cm the curve decreases fast from 3.59 V to 0.72 V. Between $2 - 5$ cm the curve decreases a bit more but only by 0.1 V each centimeter. After 5 cm the curve is relatively constant. The confidence interval is almost the same for distances between $2 - 8$ cm and relatively small for 0 and 1 cm.

In Table 11 the average V_{in} for 100 runs on each centimeter can be seen.

$Distance$ [cm]	0	1	2	3	4	5	6	7	8
$V_{in,avg}$[V]	3.59	3.18	0.72	0.65	0.56	0.34	0.38	0.39	0.46

Table 11: Average input voltage $V_{in,avg}$ for each distance from the test with the skin imitation setup for the Y1 board

The results from the test with the pork chop setup for the Y1 board can be seen in figure 36. From $2-3$ cm the curve decreases linearly from 2.66 V to 0.73 V. The curve continues to decrease but not as rapidly to 0.22 V at 6 cm. From $6-7$ cm the curve increases to 0.39 V and is almost constant between $7-8$ cm. The confidence interval is almost identical between $2-8$ cm.
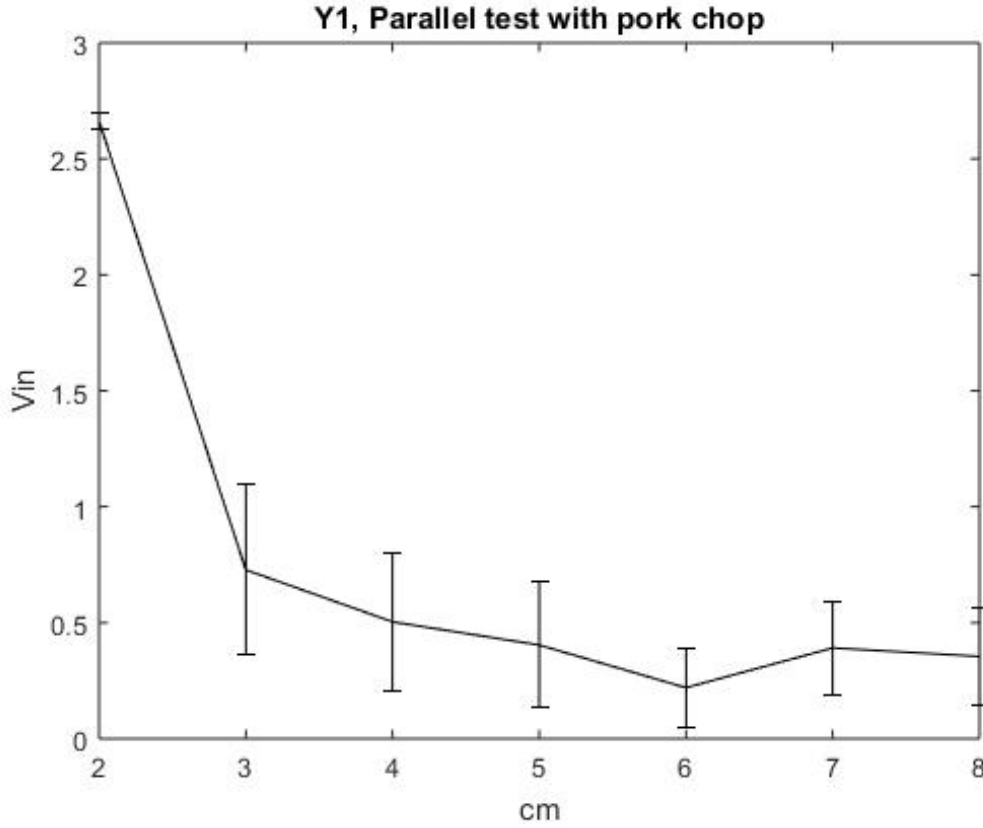
Figure 36: *Measurements with the Y1 board using the pork chop setup. The measuring starts at 2 cm. From $2-3$ cm the curve decreases linearly from 2.66 V to 0.73 V. The curve continues to decrease but not as rapidly to 0.22 V at 6 cm. From $6-7$ cm the curve increases to 0.39 V and is almost constant between $7-8$ cm. The confidence interval is almost identical between $2-8$ cm.*

In Table 12 the average V_{in} for 100 runs on each centimeter can be seen.

$Distance$[cm]	2	3	4	5	6	7	8
$V_{in,avg}$[V]	3.66	0.73	0.50	0.40	0.22	0.39	0.35

Table 12: *Average input voltage $V_{in,avg}$ for each distance from the test with the pork chop setup for the Y1 board*

The results from the test with the side by side setup for the Y1 board can be seen in figure 37. The curve does not differ significantly between the starting point at 1 cm and the last point at 8 cm. For $3-8$ cm the voltage differs by one hundred decimal places. The confidence interval does not differ much between the distances.
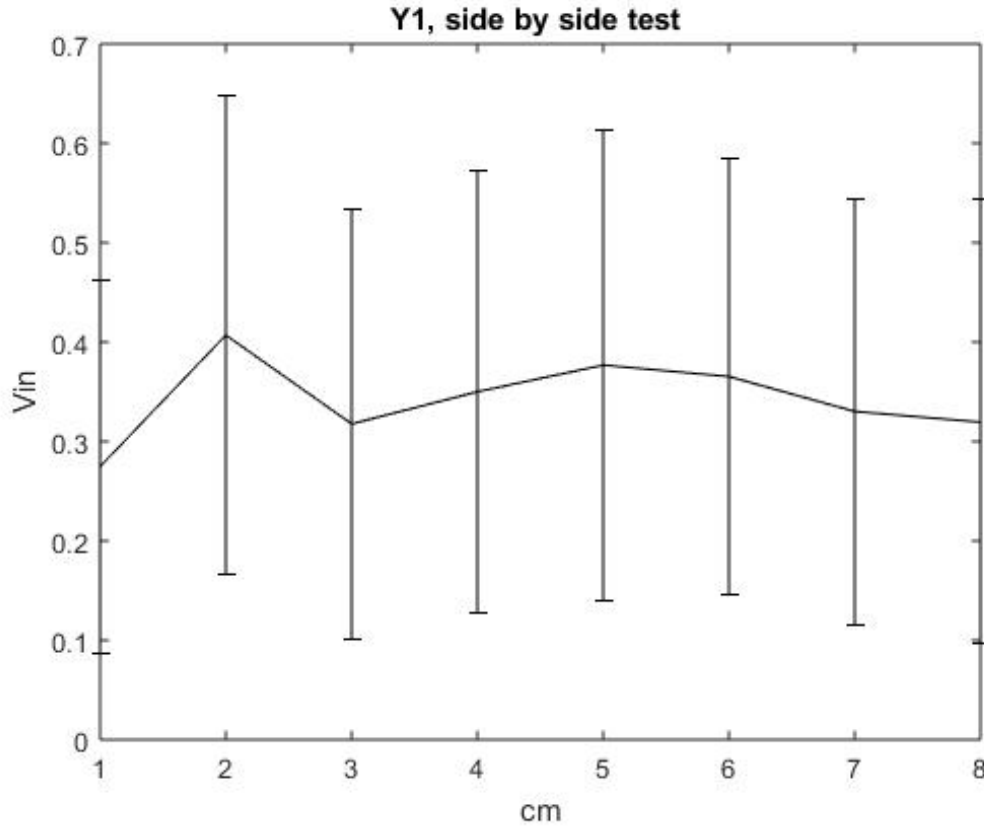
Figure 37: Measurements with the Y1 board with the side by side setup. The curve does not differ significantly between the starting point at 1 cm and the last point at 8 cm. For $3-8$ cm the voltage differs by one hundred decimal places. The confidence interval does not differ much between the distances.

In Table 13 the average V_{in} for 100 runs on each centimeter can be seen.

$Distance$ [cm]	1	2	3	4	5	6	7	8
$V_{in,avg}$[V]	0.27	0.41	0.32	0.35	0.38	0.36	0.33	0.32

Table 13: Average input voltage $V_{in,avg}$ for each distance from the test with the side by side setup for the Y1 board

6.3.3 Y2

The results from the test with the parallel setup for the Y2 board can be seen in figure 38. The tests were made for distances between $2 - 8$ cm because the board had a lot of components on it. The voltage decreases almost linearly between $2 - 5$ cm with a voltage drop from 3.54 V to 0.58 V. Between $5 - 6$ cm and $7 - 8$ cm the voltage is more or less constant. There is a voltage drop between $6 - 7$ cm from $0.67 - 0.34$ V. The confidence interval is almost the same and larger for distances between $5 - 8$ cm.
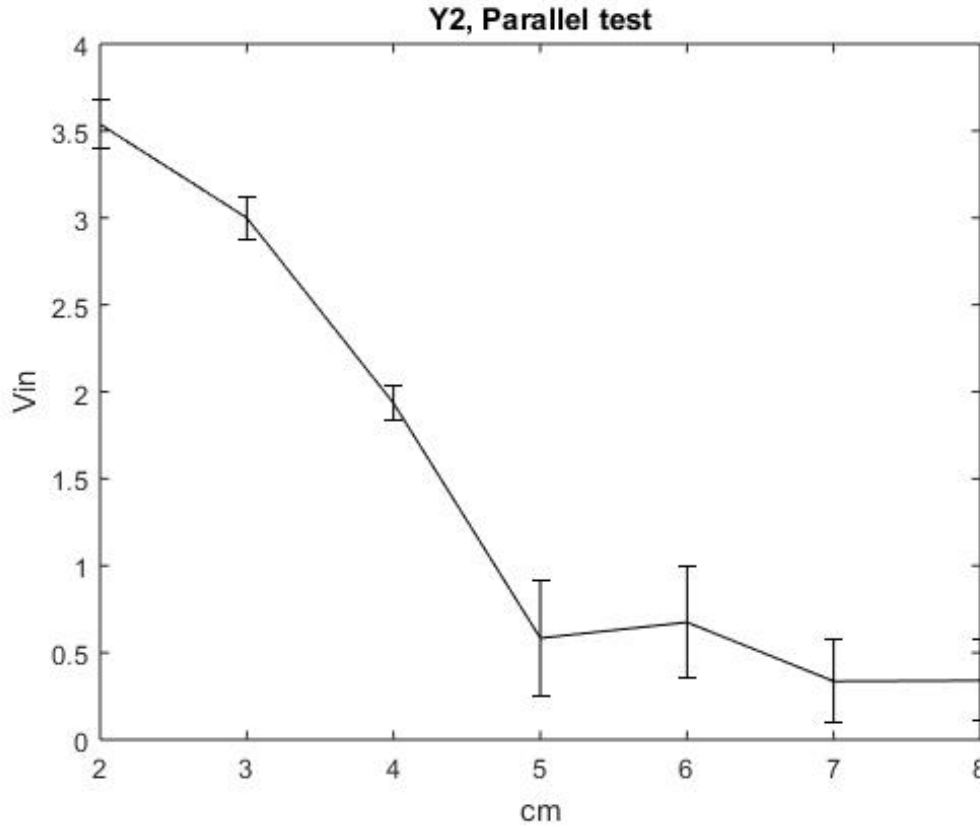
Figure 38: Measurements with the Y2 board with the parallel setup. The voltage decreases almost linearly between $2 - 5$ cm with a voltage drop from 3.54 V to 0.58 V. Between $5 - 6$ cm and $7 - 8$ cm the voltage is more or less constant. There is a voltage drop between $6 - 7$ cm from $0.67 - 0.34$ V. The confidence interval is almost the same and larger for distances between $5 - 8$ cm.

In Table 14 the average V_{in} for 100 runs on each centimeter can be seen.

$Distance$ [cm]	2	3	4	5	6	7	8
$V_{in,avg}$[V]	3.54	3.00	1.93	0.58	0.67	0.34	0.34

Table 14: Average input voltage $V_{in,avg}$ for each distance from the test with the parallel setup for the Y2 board

The results from the test with the angled setup for the Y2 board can be seen in figure 39. The voltage drops linearly from $3.19 - 0.54$ V between $2 - 4$ cm. Between $4 - 8$ cm the curves is quite constant with voltages around 0.4 V. The confidence interval is almost the same and larger for the distances $4 - 8$ cm.
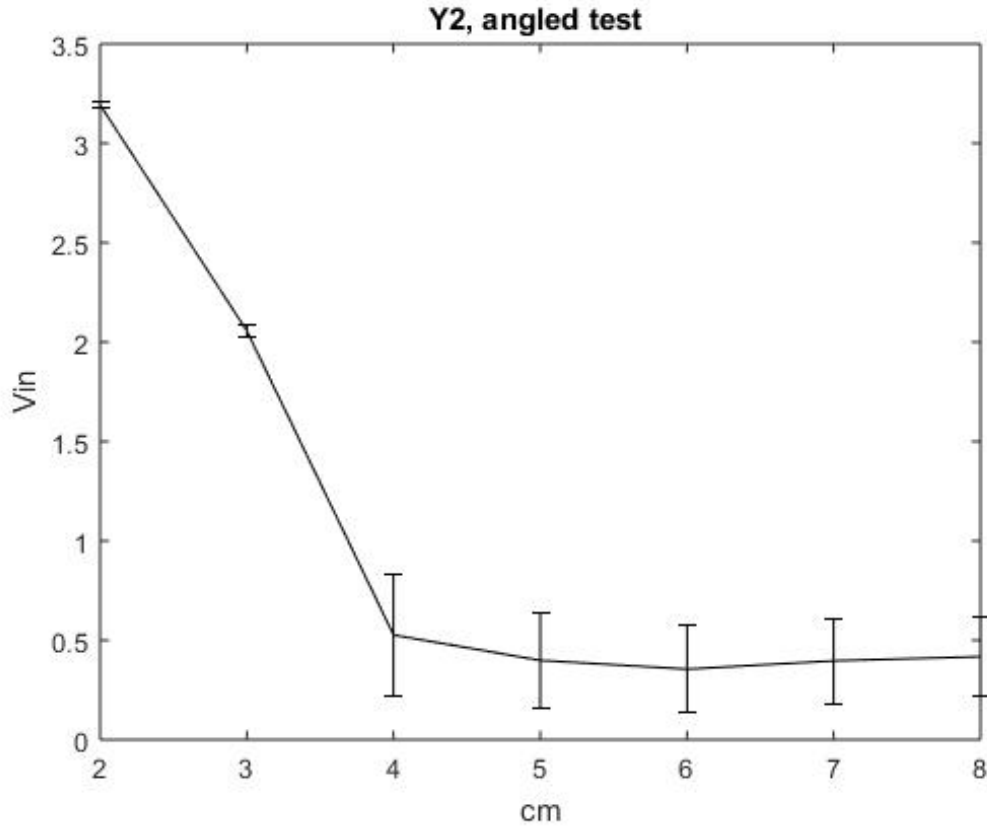
Figure 39: Measurements with the Y2 board with the $45°$ setup. The voltage drops linearly from $3.19 - 0.54$ V between $2 - 4$ cm. Between $4 - 8$ cm the curves is quite constant with voltages around 0.4 V. The confidence interval is almost the same and larger for the distances $4 - 8$ cm.

In Table 15 the average V_{in} for 100 runs on each centimeter can be seen.

$Distance$ [cm]	2	3	4	5	6	7	8
$V_{in,avg}$[V]	3.19	2.06	0.53	0.40	0.35	0.40	0.42

Table 15: Average input voltage $V_{in,avg}$ for each distance from the test with the angled setup for the Y2 board

The results from the test with the skin imitation for the Y2 board can be seen in figure 40. Between $2 - 5$ cm the curve is decreasing linearly from $3.5 - 0.6$ V. Between $5 - 8$ cm the voltage is almost constant but is slightly decreasing. The confidence interval for the distances $5 - 8$ cm is almost the same and larger than for the other distances.
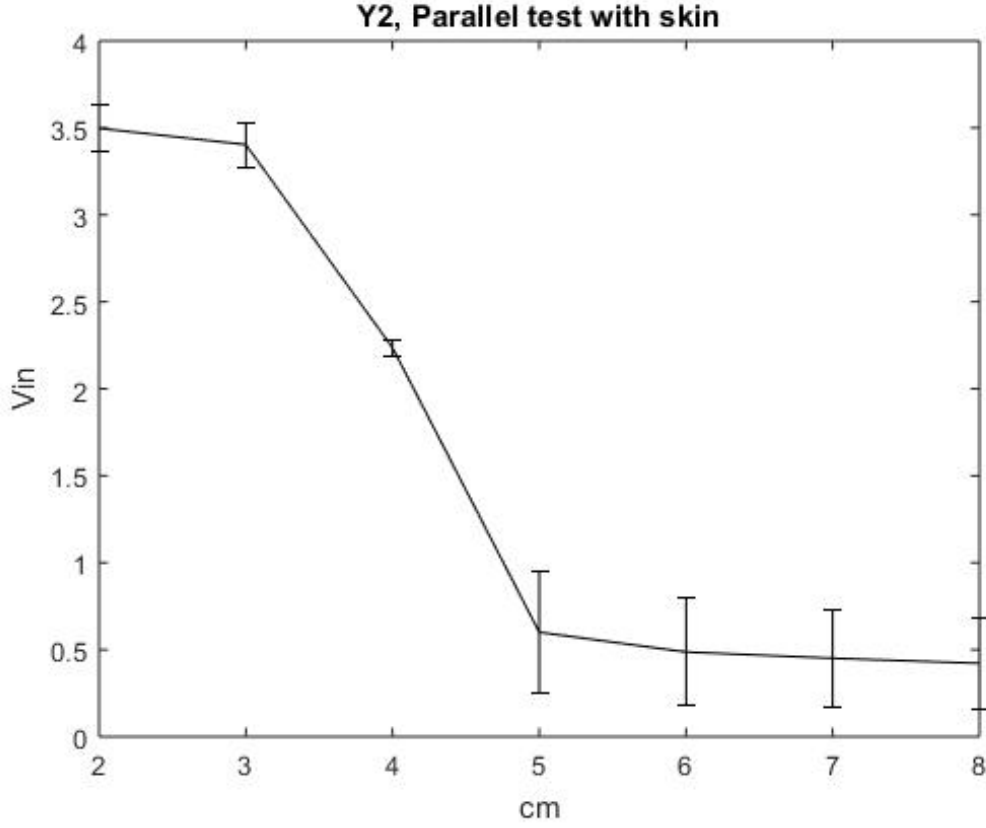
Figure 40: Measurements with the Y2 board with the skin imitation setup. Between $2 - 5$ cm the curve is decreasing linearly from $3.5 - 0.6$ V. Between $5 - 8$ cm the voltage is almost constant but is slightly decreasing. The confidence interval for the distances $5 - 8$ cm is almost the same and larger than for the other distances.

In Table 16 the average V_{in} for 100 runs on each centimeter can be seen.

$Distance$ [cm]	2	3	4	5	6	7	8
$V_{in,avg}$[V]	3.50	3.40	2.24	0.60	0.49	0.45	0.42

Table 16: Average input voltage $V_{in,avg}$ for each distance from the test with the skin imitation for the Y2 board

The results from the test with the pork chop for the Y2 board can be seen in figure 41. Between $2-3$ cm there is a small voltage drop from $3.48-3.32$ V. Between $3-5$ cm the voltage decreases linearly from $3.32-0.92$ V. Between $5-8$ cm the curve is almost constant aside from a small drop in voltage between $5-6$ cm. The confidence interval is almost the same and larger for $5-8$ cm than the other distances.
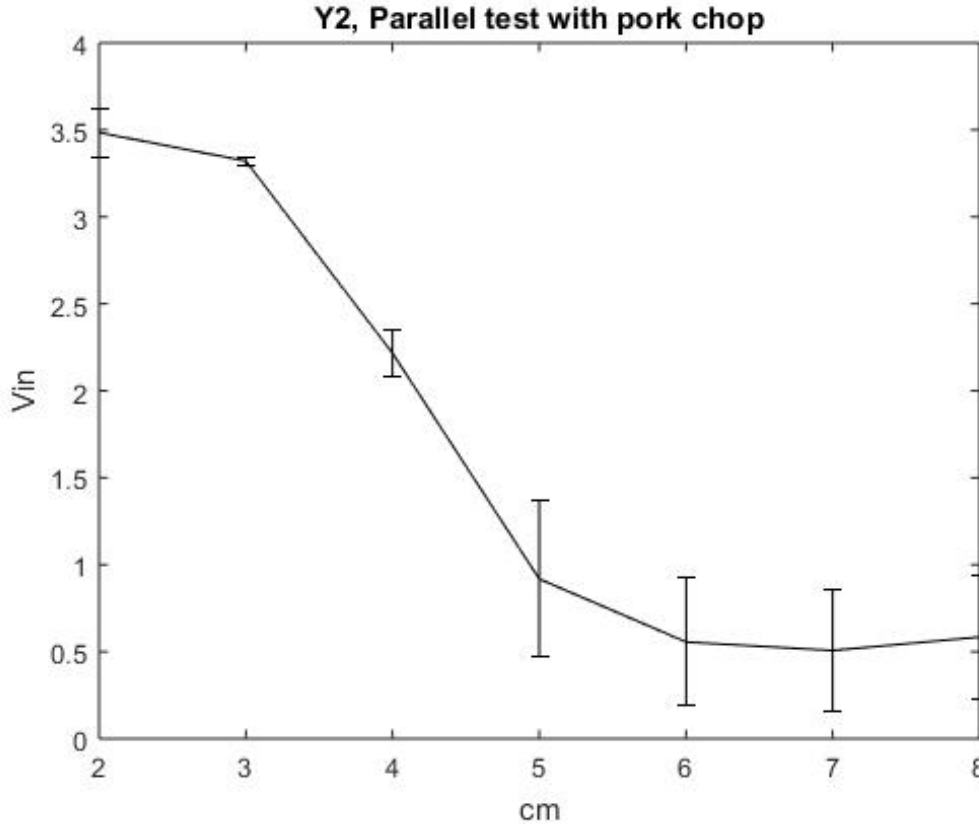
Figure 41: Measurements with the Y2 board with the pork chop setup. Between $2-3$ cm there is a small voltage drop from $3.48-3.32$ V. Between $3-5$ cm the voltage decreases linearly from $3.32-0.92$ V. Between $5-8$ cm the curve is almost constant aside from a small drop in voltage between $5-6$ cm. The confidence interval is almost the same and larger for $5-8$ cm than the other distances.

In Table 17 the average V_{in} for 100 runs on each centimeter can be seen.

$Distance$ [cm]	2	3	4	5	6	7	8
$V_{in,avg}$[V]	3.48	3.32	2.22	0.92	0.55	0.51	0.58

Table 17: Average input voltage $V_{in,avg}$ for each distance from the test with the skin imitation for the Y2 board

The results from the test with the side by side setup for the Y2 board can be seen in figure 42. The voltages vary in a very small interval from $0.35 - 0.21$ V and the confidence interval is almost the same for all the distances.
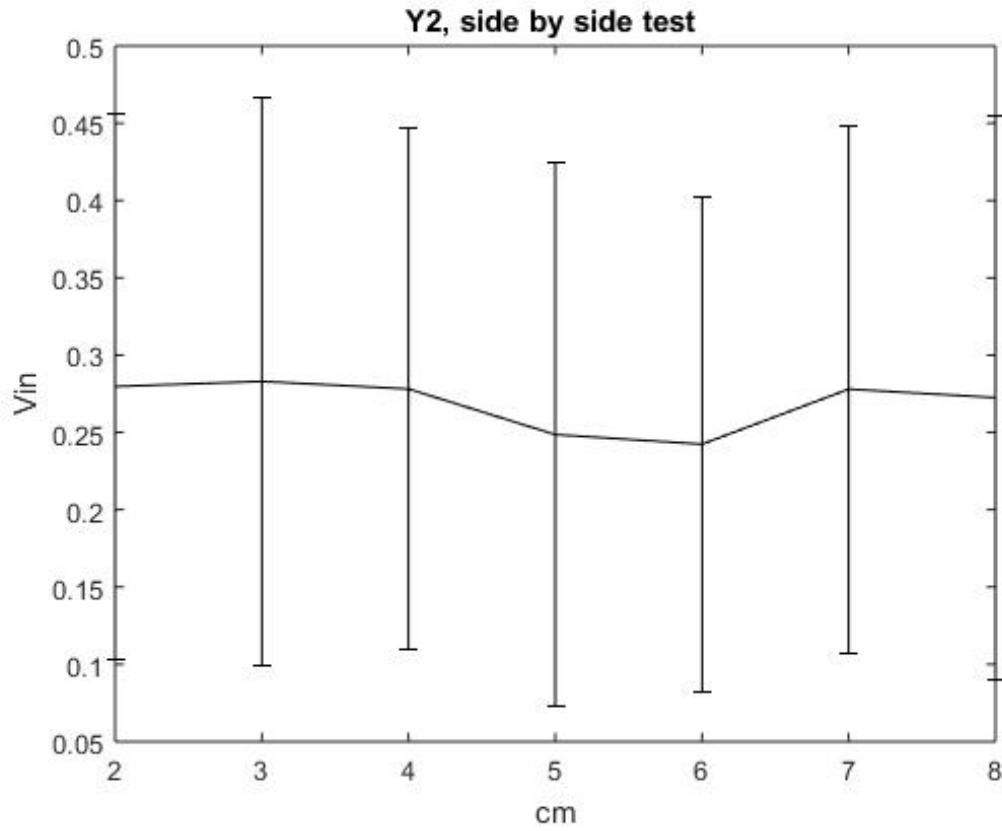
Figure 42: Measurements with the Y2 with the side by side setup. The voltages vary in a very small interval from $0.35 - 0.21$ V and the confidence interval is almost the same for all the distances.

In Table 18 the average V_{in} for 100 runs on each centimeter can be seen.

$Distance$ [cm]	2	3	4	5	6	7	8
$V_{in,avg}$[V]	0.24	0.32	0.22	0.35	0.23	0.21	0.27

Table 18: Average input voltage $V_{in,avg}$ for each distance from the side by side setup for the Y2 board

6.3.4 Ams

The parallel test and the test with the skin imitation is measured from $1 - 8$ cm, due to that the setup does not allow the boards to completely touch each other. The tests with the $45°$ and pork chop setup are also measured between $2 - 8$ cm due to the setup limitations. The results from the test with the parallel setup for the Ams board can be seen in figure 43. The curve is quite stable the voltage vary between $3.64 - 3.58$ V with a higher confidence interval at 3, 5 and 8 cm.
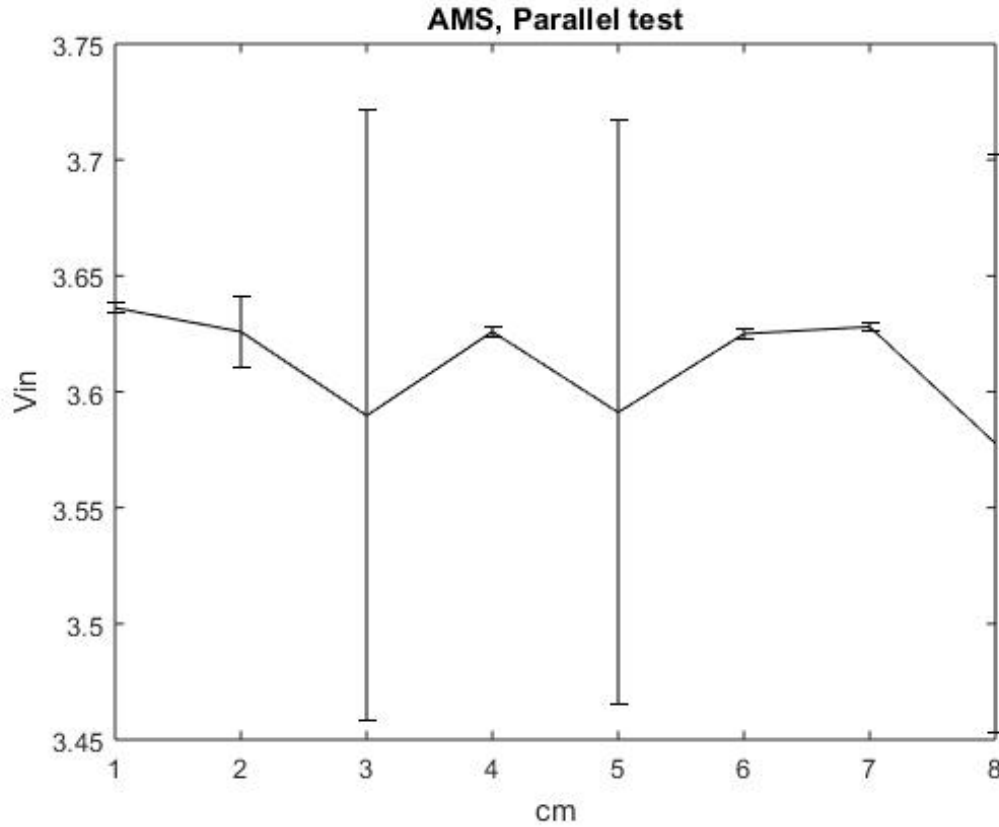
Figure 43: Measurements with the Ams board with the parallel setup. The curve is quite stable the voltage vary between $3.64 - 3.58$ V with a higher confidence interval at 3, 5 and 8 cm.

In Table 19 the average V_{in} for 100 runs on each centimeter can be seen.

$Distance$ [cm]	1	2	3	4	5	6	7	8
$V_{in,avg}$[V]	3.64	3.63	3.59	3.62	3.59	3.62	3.63	3.58

Table 19: Average input voltage $V_{in,avg}$ for each distance from the test with the parallel setup for the Ams board

The results from the test with the angled setup for the Ams board can be seen in figure 44. Between $2 - 6$ cm the curve is fairly constant and has a voltage around 3.6 V. Between $6 - 8$ cm there is a voltage drop that is nearly linear with a voltage of 2.97 V at 8 cm. The confidence interval is larger at 3, 5, 6 and 7 cm.
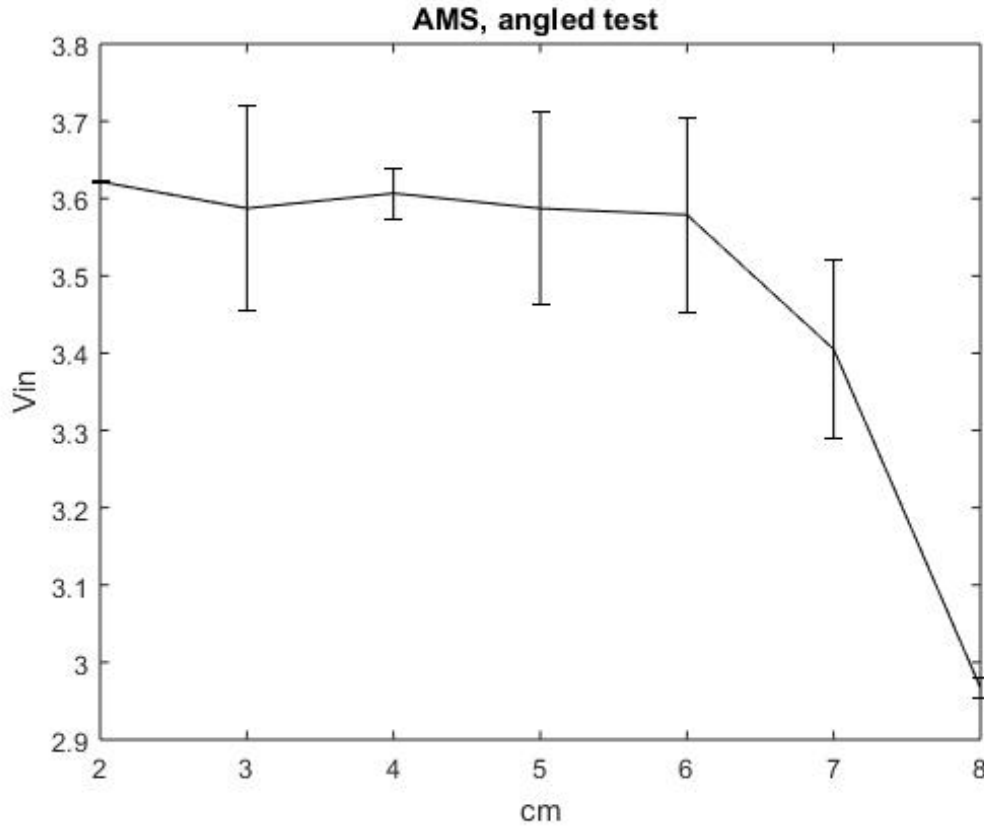
Figure 44: Measurements with the Ams board with the 45° setup. Between $2-6$ cm the curve is fairly constant and has a voltage around 3.6 V. Between $6-8$ cm there is a voltage drop that is nearly linear with a voltage of 2.97 V at 8 cm. The confidence interval is larger at 3, 5, 6 and 7 cm.

In Table 20 the average V_{in} for 100 runs on each centimeter can be seen.

$Distance$ [cm]	2	3	4	5	6	7	8
$V_{in,avg}$[V]	3.62	3.59	3.61	3.59	3.58	3.40	2.97

Table 20: Average input voltage $V_{in,avg}$ for each distance from the test with the angled setup for the Ams board

The result from the test with the skin imitation for the Ams board can be seen in figure 45. The voltage is quite constant, it varies between $3.63 - 3.59$ V. The confidence interval is larger at 1, 2, 5, 6 and 8 cm.
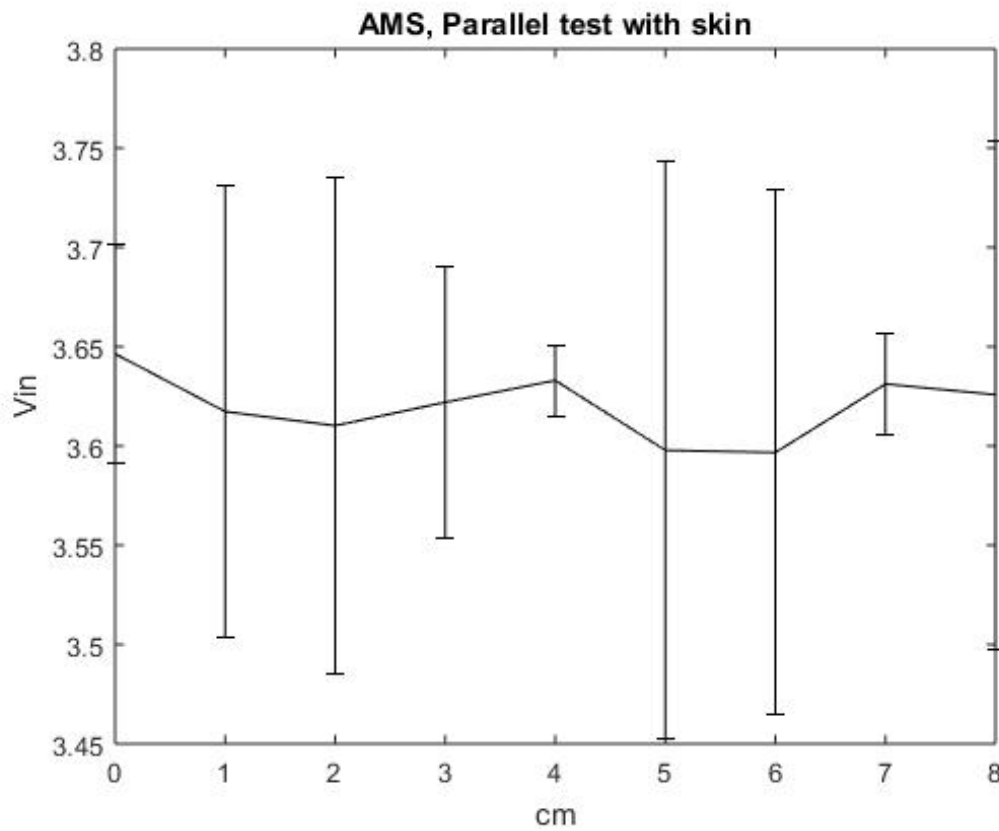
Figure 45: Measurement with the Ams board with the skin imitation setup. The voltage is quite constant, it varies between $3.63 - 3.59$ V. The confidence interval is larger at 1, 2, 5, 6 and 8 cm.

In Table 21 the average V_{in} for 100 runs on each centimeter can be seen.

$Distance$ [cm]	1	2	3	4	5	6	7	8
$V_{in,avg}$[V]	3.62	3.61	3.62	3.63	3.60	3.59	3.63	3.62

Table 21: Average input voltage $V_{in,avg}$ for each distance from the test with the skin imitation for the Ams board

The results from the test with the pork chop for the Ams board can be seen in figure 46. The curve is relatively constant, the voltage varies between $3.65 - 3.61$ V. The confidence interval is larger at 5 and 7 cm.
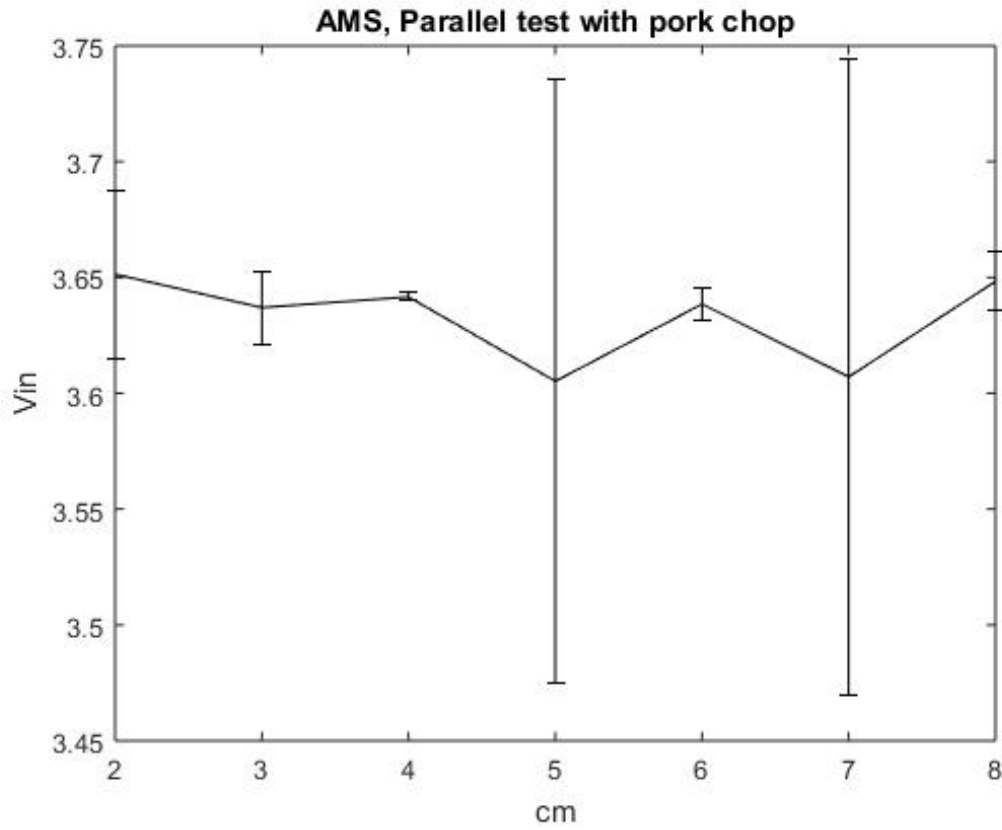
Figure 46: Measurements with the Ams board with the pork chop setup. The curve is relatively constant, the voltage varies between $3.65 - 3.61$ V. The confidence interval is larger at 5 and 7 cm.

In Table 22 the average V_{in} for 100 runs on each centimeter can be seen.

$Distance$ [cm]	2	3	4	5	6	7	8
$V_{in,avg}$[V]	3.65	3.64	3.64	3.61	3.63	3.61	3.65

Table 22: Average input voltage $V_{in,avg}$ for each distance from the test with the pork chop for the Ams board

The results from the test with the side by side setup for the Ams board can be seen in figure 47. Between $1 - 3$ cm the voltage decreases linearly from $3.5 - 0.46$ V. Between $3 - 5$ cm the voltage increases to a value of 2.24 V. Between $5 - 8$ cm the voltage is almost constant. The confidence interval is larger at 2, 5, 6 and 7 cm.
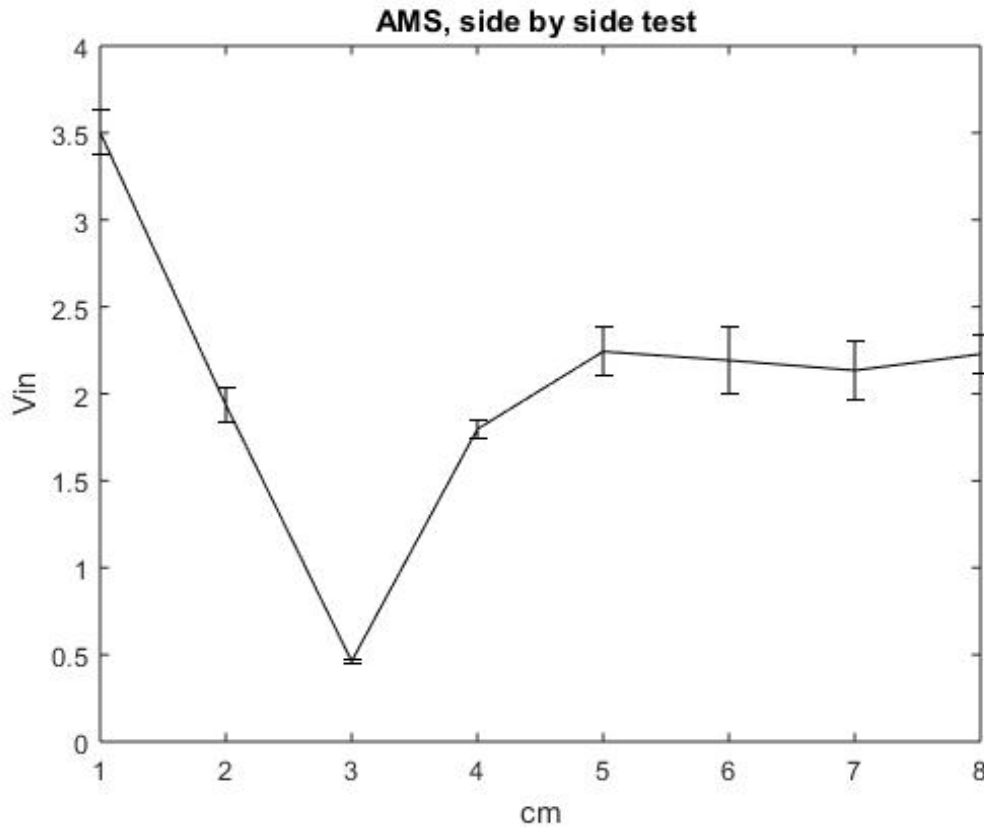
Figure 47: *Measurements with the Ams board with the side by side setup. Between $1 - 3$ cm the voltage decreases linearly from $3.5 - 0.46$ V. Between $3 - 5$ cm the voltage increases to a value of 2.24 V. Between $5 - 8$ cm the voltage is almost constant. The confidence interval is larger at 2, 5, 6 and 7 cm.*

In Table 23 the average V_{in} for 100 runs on each centimeter can be seen.

$Distance$ [cm]	1	2	3	4	5	6	7	8
$V_{in,avg}$[V]	3.50	1.94	0.46	1.79	2.24	2.19	2.14	2.23

Table 23: *Average input voltage $V_{in,avg}$ for each distance from the test with the side by side setup for the Ams board*

7 Discussion

The theoretical and practical results will be discussed in this chapter. The ethical aspect as well as the reliability of sources of information used in this project will also be discussed.

7.1 Theoretical results

The theoretical calculations are presented in the section 6 in Figure 23 and 22. The theoretical calculations were done with some common parameters for all the boards. The material in the antennas and the efficiency of EH:s are the same for all the different boards because the information could not be found. During the project there have been multiple attempts to get in touch with the manufacturer of the Ams and the red board. We have sent the companies multiple emails and called without them getting back to us. The results from the theoretical calculated efficiency are therefore more of a comparison on how the different shapes affect the efficiency.

In Figure 23 the efficiency can be seen for all the boards over different distances. The efficiency of all boards are affected by the distance and will decrease exponentially when the distance increases. Around 10 cm the efficiency is close to zero. A nerve stimulation chip has to be implemented superficially under the skin for the given boards.

All the boards are calculated for when the Rx board is centered over the Tx board. When the distance between Rx and Tx boards is zero, there will be a distance between the coils depending on the size difference between the Rx board and the Tx board. By placings the Rx boards next to the Tx it can be seen how well the coils match. This comparison can be seen in Figure 48.
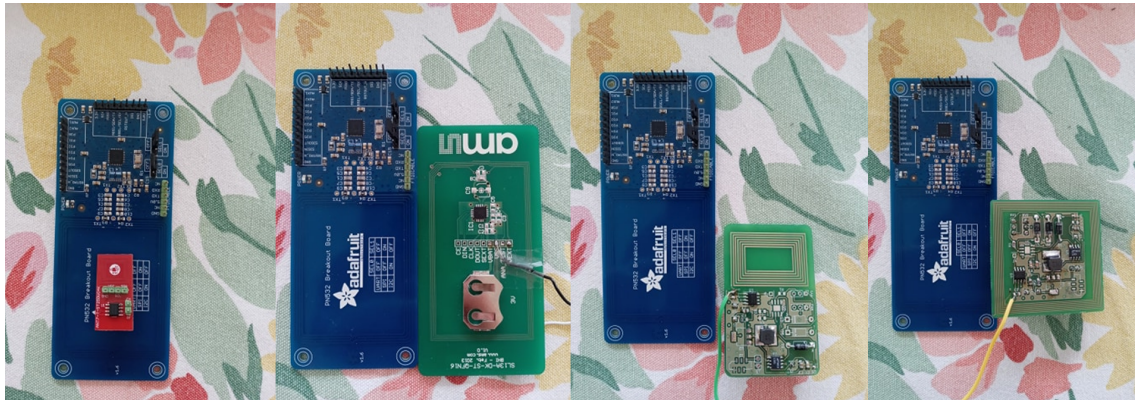
Figure 48: The four different Rx boards next to the Tx board with a size comparison of the antennas.

The boards are listed in order of how much contact or distance the board has to the coil on the Tx board. The order is Y2, Ams, Y1 and the red board. The efficiency for the boards can be seen in Figure 23. When the distance is zero the board will have different efficiency. The boards from highest to lowest efficiency are listed as Y2, Ams, Y1 and the red board.

According to this observation a Rx with the same measurement as the Tx, should have higher efficiency at a low distance. The efficiency is calculated for a board with the same parameter as for the Y2 in order to test this observation, the height and width are not the same as for the Y2 board. The original Y2 board is plotted as a reference, and is a smaller board than the Tx. Calculations are also done for Y2, one with coils the same size as Tx and one with coils two times larger than Tx. The Matlab code for the comparison of different sized Y2 can be seen in appendix J.

The result of the calculations can be seen in Figure 49. For the efficiency at zero centimeters, the Y2 board which is the same size as the Tx will be a bit more efficient than the original Y2 board. The larger modified Y2 board has a lower efficiency. But the larger antenna has the highest efficiency for distances larger than 0.5 cm. The size of the antenna will be a design parameter dependent on what distance the antenna should work at.
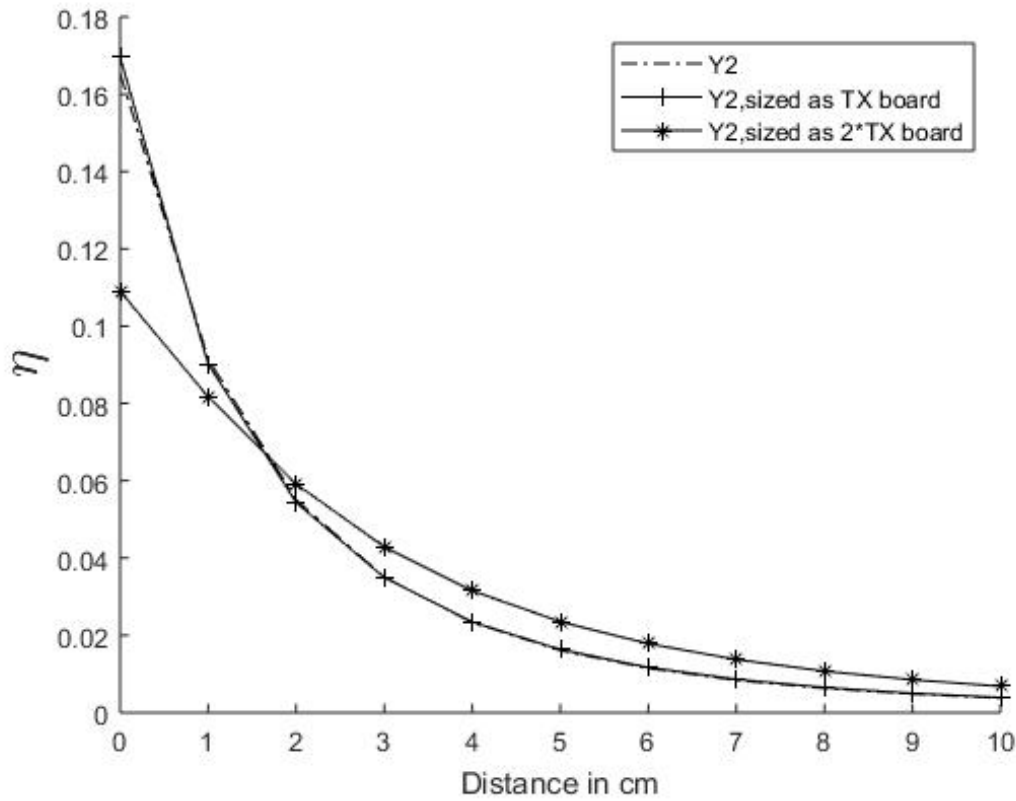
Figure 49: Graph over the efficiency over the different distances for the Y2 board. The graph has three different curves, one of the Y2 board unmodified, one where the Y2 has the same size as the Tx, and one where the Y2 board is twice the size of the Tx board.

Due to that the efficiency drops exponential the Tx has to send out exponentially higher power to keep a constant current in the Rx. The power that the sender needs to send out to keep 1 mA in the Rx can be seen in Figure 22.

7.2 Comparison of the practical tests

The graphs of the practical test and the theoretical calculations can be seen in section 6. The curves in the practical tests are not exponential as the theoretical graph are, which can be seen in Figure 23. That because the outputs are measured after an EH which has a constant output [29]. The theoretical and practical results are not expected to be identical, but theoretical values will indicate on how the antenna shape effects boards efficiency. The Ams board has a different sort of EH than the rest of the Rx boards. The Rx boards output is considered good if the input voltages are strong enough to turn on the EH.

To compare the different results, one graph for each test setup has been made. The tests with the fewest measuring points were the ones limiting the number of points on the x-axis. This means that the Figures 50, 51, 52 and 53 have an x-axis starting on 2 cm instead of 0 cm. Figure 54 has an x-axis starting at 1 cm instead of 2 cm. The curves contain the confidence interval and it is represented by a vertical line at each measuring point on the x-axis.

7.2.1 Comparison of the parallel test

The results from the test with the parallel setup for all the boards combined in one graph can be seen in Figure 50.
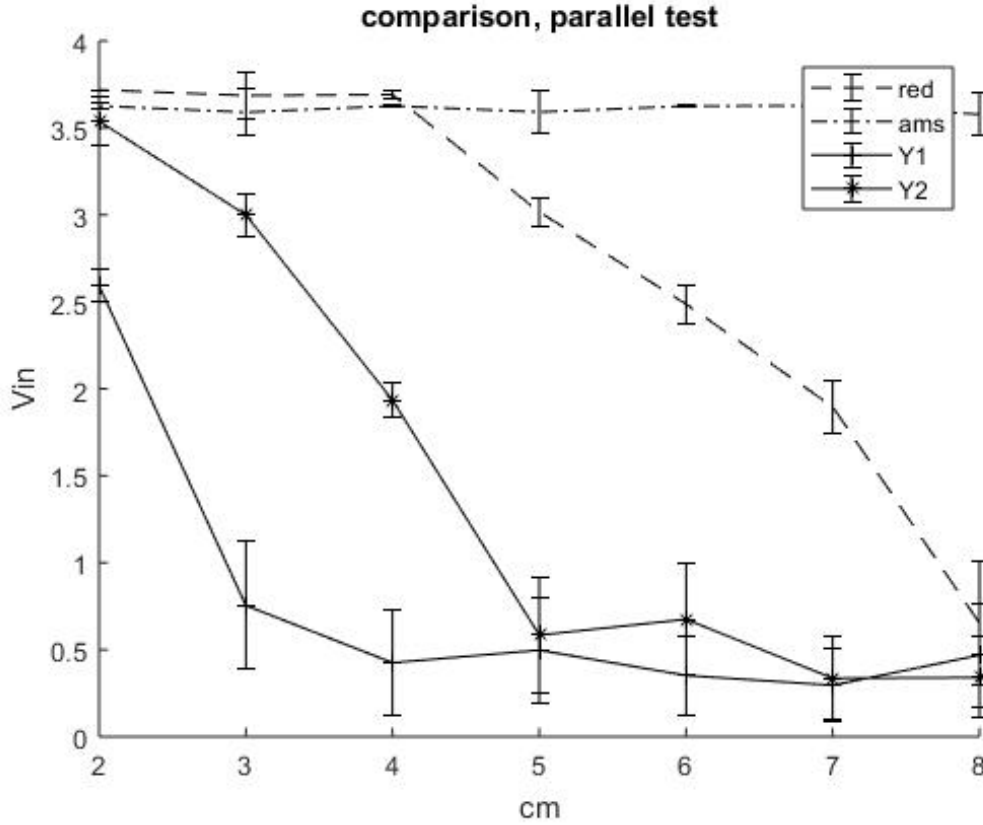
Figure 50: Curves on the parallel setup for all the boards. The Ams board is the most stable board compared to the others but the red board has the highest output from 2 − 4 cm. The Y1 board has the lowest output voltage for all the distances.

It can be seen from Figure 50 that the Ams board is the most stable one. The red board will give a higher output than the Ams board when the EH is active. The output from the Ams EH may have a lower output and that could give a lower threshold value for the Ams EH. A lower threshold value could be one reason why the Ams board can hold a constant output for larger distances.

It can be seen that the Ams board is the largest board and in combination with Figure 48, which shows that bigger antennas have higher efficiency, it could explain why the output is very stable. The other boards, Y1, Y2 and the red one, have the same EH. Y1 and Y2 should be more efficient than the red board according to the results in Figure 23. The higher efficiency should fulfill the EH threshold value for larger distances. The practical test shows that the red board is more efficient than Y1 and Y2, which can be seen in Figure 50. The theoretical calculations of the red board were done assuming that the material of the antenna is gold since the material for the antenna was unknown [32]. The coupling factor is a percentage value of the efficiency between Rx and Tx. From the equation 3 which describes the coupling factor, it is known that a lower inductance value in the Rx board will contribute to a larger coupling factor. The inductance in the Rx coil depends on the relative permeability of the material in the antenna [37], which means that the red board should have a lower relative permeability than gold, according to Figure 50.

The confidence interval for Y1 and Y2 is bigger than for the Ams and the red board which shows that the output from those board are less stable than for the other boards.

7.2.2 Comparison of the angled test

The result from the test with the angled setup for all the boards combined in one graph can be seen in Figure 51.
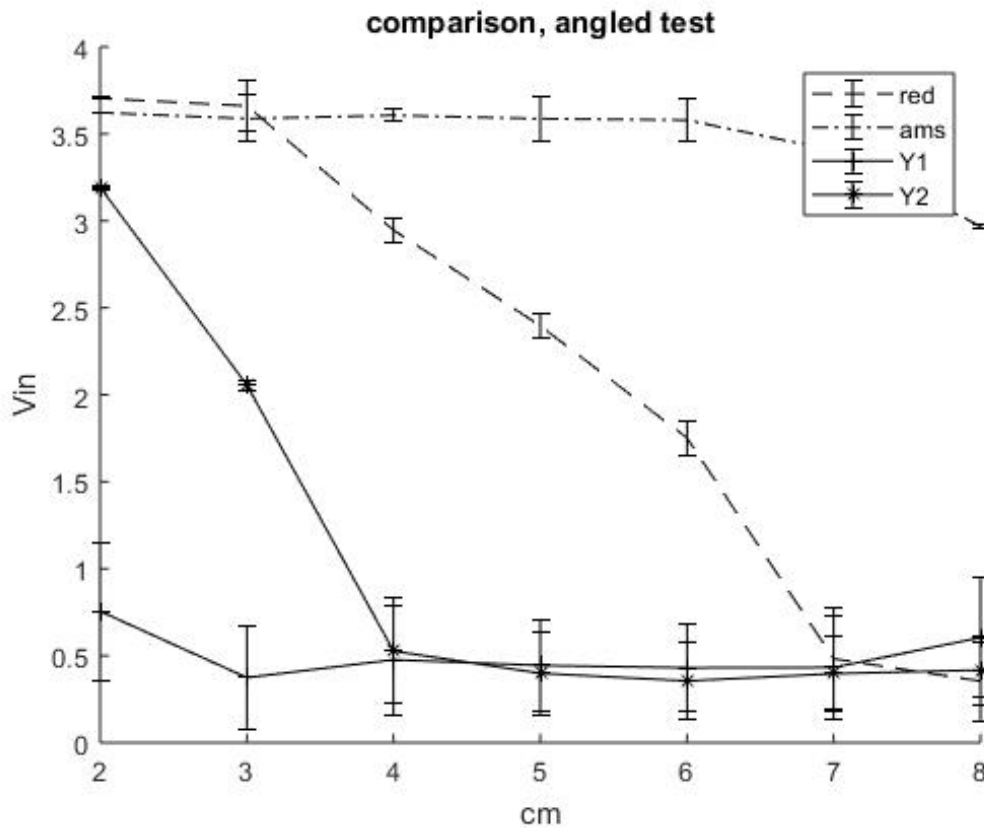
Figure 51: Curves on the angled setup for all the boards. The Ams board is the most stable board compared to the other but the red board has the highest output from $2 - 3$ cm. The Y1 board has the lowest output voltage for all the distances.

From Figure 51 it can be seen that the Ams board is the most stable board. All boards have in common that the voltage start to drop at a smaller distance compared to the parallel test, see the parallel test in Figure 50. Otherwise the results are similar regarding the boards stability.

7.2.3 Comparison of the skin imitation test

The results from the test with the side skin imitation setup for all the boards combined in one graph can be seen in Figure 52.
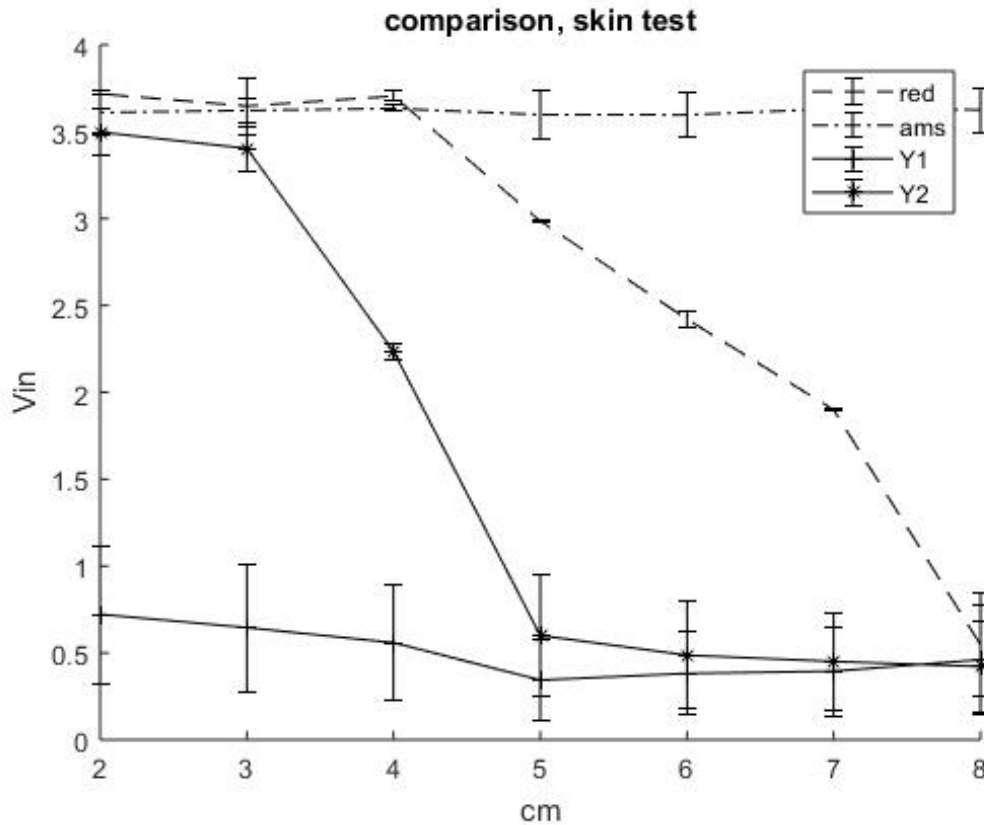
Figure 52: Curves on the skin imitation setup for all the boards. The Ams board is the most stable board compared to the others but the red board has the highest output from 2 − 4 cm. The Y1 board has the lowest output voltage for all the distances.

From Figure 52 it can be seen that the boards outputs are fairly similar to the parallel test which can be seen in Figure 52. The skin is not an inductive material and will therefore not affect the wireless power transfer. Y1 differs a bit which may be because the skin imitation was placed on the Y1 board instead of the Tx as it where for the other test. The extra weight from the skin imitation could have affected the stepper motor and the position of the test points may not have been as accurate as for the parallel test. The Y1 board was not retested due to the ongoing corona pandemic. The region of Östragötaland has issued a self quarantine which has affected the ability to run the test again, the restriction is to work from home and the material could not be retrieved from the office.

7.2.4 Comparison of the pork chop test

The result from the test with the pork chop setup for all the boards combined in one graph can be seen in Figure 53.
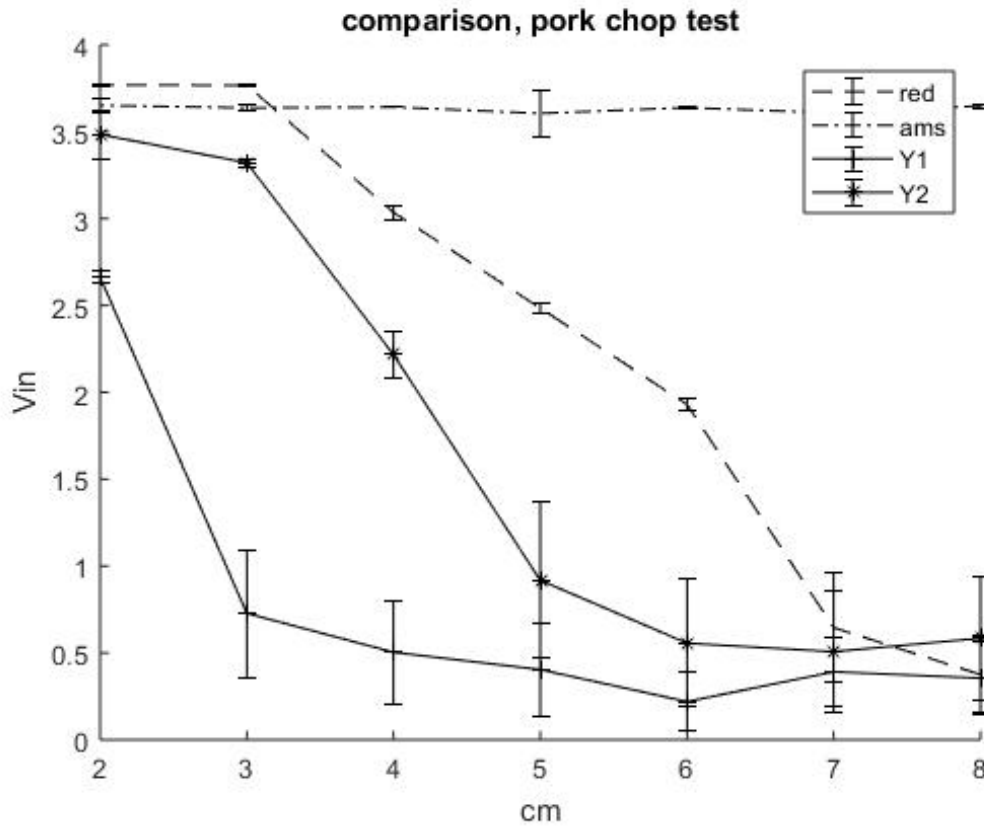
Figure 53: Curves on the pork chop setup for all the boards. The Ams board is the most stable board compared to the other but the red board has the highest output from $2-3$ cm. The Y1 board has the lowest output voltage for all the distances.

The output in Figure 53 is similar to the parallel test which can be seen in Figure 50. The output voltage starts to drop at a smaller distance compared to the parallel test which could be because of the setup. The board was bent when it touched the pork chop. The result was the same behavior as in the angled test, see the angled test in Figure 51. The pork chop is not an inductive material and does therefore not affect the wireless power transfer.

7.2.5 Comparison of the side by side test

The results from the test with the side by side setup for all the boards combined in one graph can be seen in Figure 54.
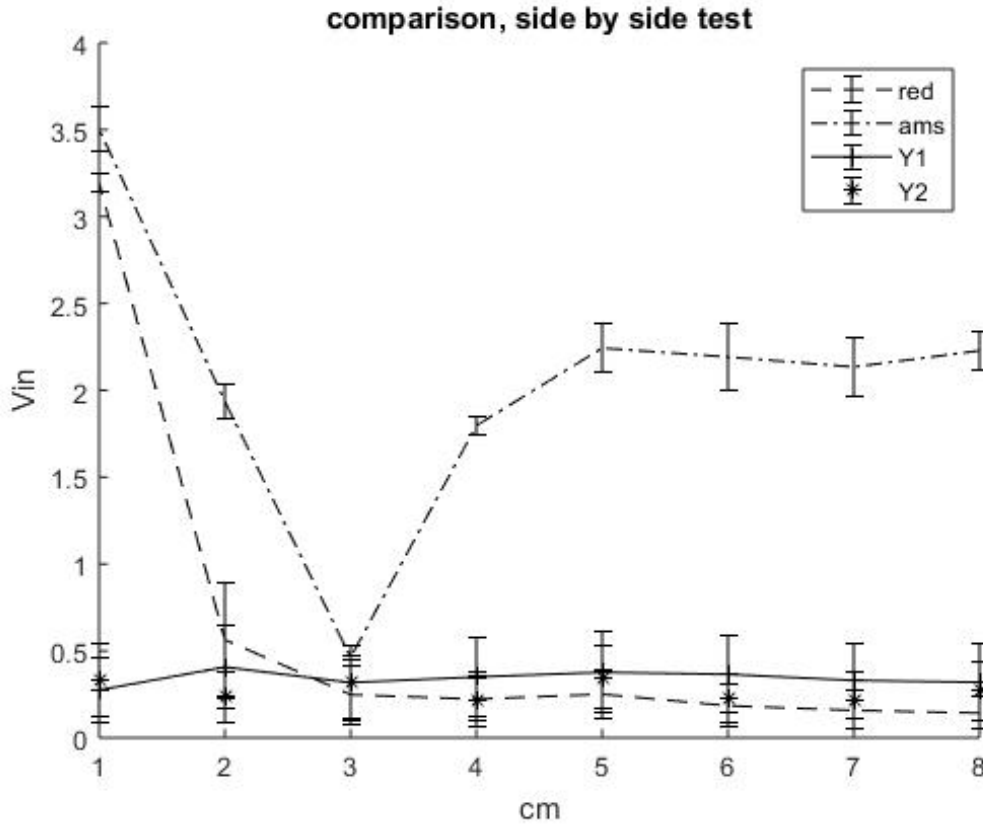
Figure 54: Curves on the side by side setup for all the boards. The Ams board is the most stable board compared to the other. The Y1 and Y2 board has the lowest output voltage for all the distances.

The red and the ams board can activate the EH at 1 cm distance and the output voltage drops significantly when the distance increases. The ams board will go down at 3 cm then start to go up and stabilize around 2 V as the distance goes from $4 - 8$ cm. The ams board may have a blind spot at 3 cm where no mutual inductance is obtained and when the distance increased it escaped the blind spot. The ams board has been the most stable board for all the other tests and should therefore have an advantage to get connection whereas it is harder for the other boards.

The mutual inductance will be lower if the Tx and Rx are not centered. The coupling factor can be seen from equation 3 and it is only effected by three parameters, the mutual inductance, inductance for Tx and Rx. The inductance is constant for each coil which indicates that the mutual inductance is affected by the location of the boards.

7.2.6 Sources of error for the tests

There were 100 tests made on each setup, one test took one hour. The confidence interval could have been smaller if more test where made. We were satisfied with the 95 % confidence interval that was achieved after 100.

The test bench is automatic but between tests the user needs to exchange the board and center it to the Tx board. In this case the human factor is the biggest source of error for the test bench. For example the test with the parallel setup may not be the same for different boards, the adjustments that were done in order to get them parallel was subjective.

When performing the measurements on the boards, cords are connected between the Arduino and the Rx board. The cords can affect the magnetic field which can effect the results from the tests. The setup was made for the metal in the stepper motor to not affect the magnetic field, but the distance of which it does is unclear and can therefore be something that has affected the results as well.

The Ams board was too heavy for the stepper motor which resulted in it getting stuck. To make the motor run again the board needed a small push. The test with the Ams board had to be supervised during the whole test phase. For the test with the fake skin the skin had to be placed on the Tx because of the extra weight.

For all the tests with the pork chop the board could not get closer than 2 cm from the transmitter because of the thickness of the pork chop. So for the comparison between the tests there were fewer test points.

Because the weight of the boards affects the stepper motor differently, the precision of the motor is questioned. The test time for the lighter boards was about 64min but for the heavier Ams board the test time was around 63min. The theory is that the boards extra weight pushes the board down a bit more than the programmed step. That extra speed could have moved the test points $\approx 1,5$ %.

7.3 Voltage control

In this section a discussion around the results from the function generator is presented, and also a discussion about the circuit design.

7.3.1 Arduino and function generator

The new functionality that was implemented with the Arduino, function generator and the LEDs has some limitations. When the distance between the antenna, which was connected to the function generator, was moved to far away the connection was lost. The distance at which the connection was lost is $10 - 12$ cm depending on how fast the transmitter antenna was moved. When we did the setup and programmed it we discussed that this limitation, together with the result from the tests with the test bench, was within reasonable limits. The test as discussed earlier was measured to $8 - 10$ cm and it was decided that for this functionality the distance did not need to be any further away. In aspects of future use when the implemented chip may move around in a room or specified area, the range may need to be improved.

An other aspect of the functionality is that when the red LED is active (the voltage is to high) the voltage lowers by 0.25 V each time in the if-statement until it reaches the approved interval and the green LED is lit. This may not be enough if the input voltage is extremely high. It would be better to lower the voltage in larger steps in order to get the yellow LED to turn on (the voltages is to low) and then slowly increase it again. This aspect can be important when this functionality is implemented as a circuit. For a nerve and surrounding tissue it would be better to lower the voltage in bigger steps for high voltage values.

7.3.2 The modified limiter circuit design

The aim of the circuit was to send out a constant voltage/current and increase/decrease the output voltage/current depending on the value of the input voltage.

The modified limiter circuit does not have a feature that increases the voltage if it is too low. It can be argued that low voltages are not dangerous for a nerve and surrounding tissue. Even if the circuit does not increase the voltage, the output current is constant which is one aim of the circuit. It is more important to have a voltage decreasing function in order to not burn a nerve or surrounding tissue.

Two simulations were made, one with the input voltage set to 3 V and the other case when it was set to 4 V. The reason for the two cases was that the highest output voltage (from EH) we obtained from the practical tests with the boards was between $3 - 4$ V. We can see that for these values on V_{EH} we get a constant output level, which is verified by the current at the drain of transistor M_{LN5} in Figure 21.

In order to regulate the output voltage the transistors are sized manually, but there has to be a more efficient way to accomplish the results than changing every width of the transistors individually. The settings that was made on the transistors were set after several simulations where the width had been changed in order to obtain a reasonable output voltage for the given input voltage.

7.4 Ethical, social and environmental aspects

The thesis needs to be discussed in terms of ethical, social and environmental aspects. The circuit that the user will have under the skin can hypothetically in the future be a safety risk, due to the use of NFC to control it. A miss use of control could in the future be a challenge due to the fast development of artificial intelligence, but has so far not been a problem. Another ethical aspect is the testing of the new solution. In order for it to be used on humans, tests on animals will be needed and is a dilemma from an ethical point of view. The finished product can and will improve the quality of life for many people. The tests on animals can be argued to be for a good cause in order to improve health. The current that is sent in to a nerve is small and will therefore not do any harm on surrounding tissue of a nerve, which means that the test carried out on pigs or rats can be done in a gentle way.

7.5 Sources

The sources that have been used are peer reviewed articles and published books. An exception when the Arduino web page was used, the information that was retrieved was code and can therefore be used as a reliable source. A few Figures have been used from Wikipedia in order for easy management of copyright. Information about nerves has been collected from a hospitals web page, which can be argued to be a reliable source.

The source [20] had a statement that the stimulation settings that were used were "standard" settings for peripheral nerves and that they have been used in all clinical trials to date [20]. In this case a statement about this is hard to fulfill due to that it is hard to have read all the literature that is available on this subject. When this was discussed with the surgeons who leads the research project that this thesis project is built on, they said that no one knows the "correct" settings. Another source [21] that we used when comparing the different stimulation setting in the theory chapter (chapter 3) had some different settings used during the clinical trial. Which contradicts the statement of the source [20]. With that said, the statement is in some aspect right, due to that the settings used for electrical nerve stimulation are common but cannot be stated as it is in the article.

8 Conclusion

The conclusions from the project are presented in this chapter, as well as the answers to the research questions. From the practical test result is it concluded that the red board is most suitable for nerve stimulation due to the stable output and size of the antenna.

The amount of efficiency that can be reached for wireless power transfer will go down exponentially when the distance from the transceiver and receiver increases. To keep a constant current in the receiver, the transceiver must adapt and exponentially increase the amount of power. The amount of power depends on the design of the receiver and transceiver boards as well as the wanted current level. This is the answer to the first research question.

The efficiency between two antennas depends on the distance, shape, and material of the antennas. When striving for a high efficiency, the shape of the antenna will depend on what distances the antennas have to each other. For small distances, the receiver size should be matched to the transceiver and for larger distances, the receiver should be larger than the transceiver. Coils with low inductance will increase the efficiency of the power transformation. This is the answer to the second research question.

To increase the level of efficiency in the existing boards the energy harvester component should be exchanged in the Y1,Y2, and the red board. The Ams board had a higher stability through the test and one reason could be that the energy harvester is different compared to the other boards. This is the answer to the third and fourth research question.

No relationship between amount of power and frequency was found for nerve stimulation. The last research question was therefore not examined and no results was obtained.

9 Future work

Here are some ideas on how our work can be developed to reach a better functionality and more accurate tests.

9.1 Test bench

In the discussion section, the stepper motor is named the source of errors for the tests. To for the tests to be even more accurate (reduce the confidence interval) a new stepper motor is needed. For the ISY department to do unattended tests the stepper motor needs to be stronger and more robust. It would be beneficial if the stepper motor slider was made out of a non-conductive material instead of metal. The cables around the stepper motor can be conductive and should be put in something that does not affect the magnetic flux.

The test points and test rounds is set manually in the Arduino code and a good complement could be a Graphical User Interface (GUI), which would make it easier for the user to start the tests. The GUI could also eliminate the risk that the user accidentally changes the code.

The test bench is programmed so it measures the test points on the way towards the Tx. The code should be rewritten so it also has test points away from the Tx. That improvement would have divided the test time by two.

New antennas should be bought, where the information about the EH and the material is know. It would be helpful for the understanding of the test results.

9.2 Voltage control development

The circuit implemented in Cadence works a simulation point of view, but the next step would be to implement it in the hardware and verify the functionality. The circuit may also need a feature that increases voltages that is too low. There may also be a need for an improvement regarding the way the voltage level in the circuit is regulated. An automated way to regulate the size of the transistors depending on the input voltage would be preferable.

There is a need for more information on how much current/voltage a nerve can endure. The information up to date is not enough. When more specified information about the voltage is obtained the boards can be optimized with that in mind.

References

[1] B. staff, "Medical gallery of blausen medical 2014," *WikiJournal of Medicine*, vol. 1, no. 2, 2014, ISSN: 2002-4436. DOI: `10.15347/wjm/2014.010`.

[2] D. Purves, *Neuroscience*. OPU USA, 2012, ISBN: 9781605358413.

[3] K. Nicholls and N. D. Furness, "Peripheral nerve compression syndromes of the upper limb," *Surgery (Oxford)*, vol. 37, no. 5, pp. 288–293, 2019, ISSN: 0263-9319. DOI: `https://doi.org/10.1016/j.mpsur.2019.02.011`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S0263931919300493`.

[4] D. Grinsell and C. Keating, "Peripheral nerve reconstruction after injury: A review of clinical and experimental therapies," *BioMed Research International*, vol. 2014, 13 pages, 2014. DOI: `https://doi.org/10.1155/2014/698256`. [Online]. Available: `https://www.hindawi.com/journals/bmri/2014/698256/`.

[5] T. Gordon, N. Amirjani, D. C. Edwards, and K. M. Chan, "Brief post-surgical electrical stimulation accelerates axon regeneration and muscle reinnervation without affecting the functional measures in carpal tunnel syndrome patients," *Experimental Neurology*, vol. 223, no. 1, pp. 192–202, 2010, ISSN: 0014-4886. DOI: `https://doi.org/10.1016/j.expneurol.2009.09.020`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S0014488609004075`.

[6] K. S. Houschyar, A. Momeni, M. N. Pyles, J. Y. Cha, Z. N. Maan, D. Duscher, O. S. Jew, F. Siemers, and J. van Schoonhoven, "The role of current techniques and concepts in peripheral nerve repair," *Plastic Surgery International*, vol. 2016, p. 8, 2016. DOI: `https://doi.org/10.1155/2016/4175293`. [Online]. Available: `https://www.hindawi.com/journals/psi/2016/4175293/`.

[7] A. W. English, G. Schwartz, W. Meador, M. J. Sabatier, and A. Mulligan, "Electrical stimulation promotes peripheral axon regeneration by enhanced neuronal neurotrophin signaling," *Developmental neurobiology*, vol. 67, no. 2, pp. 158–172, 2007. DOI: `10.1002/dneu.20339`.

[8] A. C. Mendonça, C. H. Barbieri, and N. Mazzer, "Directly applied low intensity direct electric current enhances peripheral nerve regeneration in rats," *Journal of Neuroscience Methods*, vol. 129, no. 2, pp. 183–190, 2003, ISSN: 0165-0270. DOI: `https://doi.org/10.1016/S0165-0270(03)00207-3`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S0165027003002073`.

[9] E. Strommer, J. Kaartinen, J. Parkka, A. Ylisaukko-oja, and I. Korhonen, "Application of near field communication for health monitoring in daily life," in *2006 International Conference of the IEEE Engineering in Medicine and Biology Society*, 2006, pp. 3246–3249. DOI: `10.1109/IEMBS.2006.260021`.

[10] K. Curran, A. Millar, and C. Mc Garvey, "Near field communication," *International Journal of Electrical and Computer Engineering*, vol. 2, no. 3, p. 371, 2012.

[11] S. Sabah, *83% efficient asic wireless power transfer from nfc for implantable sensors*, Sep. 2020. [Online]. Available: `http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-169875` (visited on February 4, 2021).

[12] R. Want, "Near field communication," *IEEE Pervasive Computing*, vol. 10, no. 3, pp. 4–7, 2011. DOI: `10.1109/MPRV.2011.55`.

[13] G. E. Castelltort, *Design of an electrical nerve stimulator using wireless power transmission through nfc*, Sep. 2018. (visited on February 5, 2021).

[14] D. Tushie, *An introduction to nfc standards*. 2012. [Online]. Available: `https://www.icma.com/ArticleArchives/StandardsOct12.pdf` (visited on February 8, 2021).

[15] (2021). "Contactless convenience with sony felica," [Online]. Available: `https://www.sony.net/Products/felica/about/2` (visited on May 21, 2021).

[16] M. H. Rashid, *Power electronics handbook*. Academic press, 2018, pp. 1451–1496, ISBN: 978-0-12-811407-0.

[17] C. Nataraj, S. Khan, M. Habaebi, and A. Muthalif, "General analysis of resonance coupled wireless power transfer (wpt) using inductive coils," *Tehnicki Vjesnik*, vol. 25, pp. 720–726, Jun. 2018. DOI: `10.17559/TV-20160105041434`.

[18] I. Alhamrouni, M. Iskander, M. Salem, L. Awalin, A. Jusoh, and T. Sutikno, "Application of inductive coupling for wireless power transfer," *International Journal of Power Electronics and Drive Systems*, vol. 11, pp. 1109–1116, Sep. 2020. DOI: `10.11591/ijpeds.v11.i3.pp1109-1116`.

[19] H. Staff, *Electrical nerve stimulation for chronic pain*, 2020. [Online]. Available: `https://www.uofmhealth.org/health-library/tn9286` (visited on May 4, 2021).

[20] K. J. Zuo, T. Gordon, K. M. Chan, and G. H. Borschel, "Electrical stimulation to enhance peripheral nerve regeneration: Update in molecular investigations and clinical translation," *Experimental Neurology*, vol. 332, p. 113 397, 2020, ISSN: 0014-4886. DOI: `https://doi.org/10.1016/j.expneurol.2020.113397`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S0014488620302284`.

[21] T. Gordon, N. Amirjani, D. C. Edwards, and K. M. Chan, "Brief post-surgical electrical stimulation accelerates axon regeneration and muscle reinnervation without affecting the functional measures in carpal tunnel syndrome patients," *Experimental Neurology*, vol. 223, no. 1, pp. 192–202, 2010, Regeneration in the Peripheral Nervous System, ISSN: 0014-4886. DOI: `https://doi.org/10.1016/j.expneurol.2009.09.020`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S0014488609004075`.

[22] A. B. Amar, A. B. Kouki, and H. Cao, "Power approaches for implantable medical devices," *Sensors*, vol. 15, no. 11, pp. 28 889–28 914, 2007, ISSN: 1424-8220. DOI: `10.3390/s151128889`. [Online]. Available: `https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4701313/`.

[23] Y. Cheng and Y. Shu, "A new analytical calculation of the mutual inductance of the coaxial spiral rectangular coils," *IEEE Transactions on Magnetics*, vol. 50, no. 4, pp. 1–6, 2014. DOI: `10.1109/TMAG.2013.2290972`.

[24] C. Nordling and J. Österman, *Physics Handbook for Science and Engineering*. Studentlitteratur AB, 2006, ISBN: 9789144044538.

[25] G. Blom, J. Enger, G. Englund, J. Grandell, and L. Holst, *Sannolikhetsteori och statistiskteori med tillämpningar*. Studentlitteratur, 2005, ISBN: 91-44-02442-8.

[26] (2021). "Confidence interval," [Online]. Available: `https://en.wikipedia.org/wiki/Confidence_interval` (visited on April 29, 2021).

[27] A. Manson, *Ece 410: Vlsi design course lecture notes*, 2008. [Online]. Available: `https://www.egr.msu.edu/classes/ece410/mason/files/Ch2.pdf` (visited on May 7, 2021).

[28] A. Zekry, *The bipolar transistors, theory and basic applications*. January 2000.

[29] B. Martí, L. Antonio, V. Ramon, and G. David, *Battery-less soil moisture measurement system based on a nfc device with energy harvesting capability*, 2018. [Online]. Available: `https://ieeexplore.ieee.org/document/8360092` (visited on May 11, 2021).

[30] "Pin limiter diodes in receiver protectors," *EDN*, pp. 50–64, 2004.

[31] M. Shokrani, M. Khoddam, M. N. Hamidon, N. Kamsani, F. Rokhani, and S. Shafie, "An rf energy harvester system using uhf micropower cmos rectifier based on a diode connected cmos transistor," *TheScientificWorldJournal*, vol. 2014, p. 963 709, March 2014. DOI: `10.1155/2014/963709`.

[32] (2021). "Sdynamic nfc/rfid tag ic with 4-kbit, 16-kbit or 64-kbit eeprom, and fast transfer mode capability," [Online]. Available: `https://www.st.com/resource/en/datasheet/st25dv04k.pdf` (visited on May 7, 2021).

[33] O. A. Ulrike Anderwald, *Sensor-enabled rfid tags extend wireless datalogging beyond identification*, 2013. [Online]. Available: `https://datasheet.octopart.com/SL13A-DK-STQFN16-Austriamicrosystems-datasheet-20736737.pdf` (visited on May 7, 2021).

[34] (2014). "Sl13a smart sensory tag chip for unique identification, monitoring and data logging," [Online]. Available: `https://www.pmt-fl.com/uploads/2018/03/precision-measurement-sl13a-datasheet-en-v4.pdf` (visited on May 9, 2021).

[35] N. Semiconductors, *Pn532/c1 near field communication (nfc) controller*, November 2007. [Online]. Available: `https://www.nxp.com/docs/en/nxp/data-sheets/PN532_C1.pdf` (visited on May 7, 2021).

[36] (2020). "Adafruit pn532 rfid/nfc breakout and shield," [Online]. Available: `https://cdn-learn.adafruit.com/downloads/pdf/adafruit-pn532-rfid-nfc.pdf?timestamp=1620029156` (visited on May 3, 2021).

[37] (2021). "Rectangle loop inductance calculator," [Online]. Available: `https://www.allaboutcircuits.com/tools/rectangle-loop-inductance-calculator/` (visited on April 8, 2021).

[38] (2018). "Motor shiled," [Online]. Available: `https://store.arduino.cc/arduino-motor-shield-rev3` (visited on April 7, 2021).

[39] (2018). "Stepper speed control," [Online]. Available: `https://www.arduino.cc/en/Tutorial/LibraryExamples/StepperSpeedControl/` (visited on April 1, 2021).

[40] (2019). "Analogread()." [Online]. Available: `https://www.arduino.cc/reference/en/language/functions/analog-io/analogread/` (visited on April 1, 2021).

[41] R. Meier, *Roger meier´s freeware*, 2021. [Online]. Available: `http://freeware.the-meiers.org/` (visited on April 28, 2021).

[42] R. Candido, *Arduino with python: How to get started*, 2019. [Online]. Available: `https://realpython.com/arduino-python/` (visited on April 29, 2021).

A Arduino code for test bench

```
//All declerations are done here, some libarys are included in order
run the motor.
#include <Stepper.h>
#include <stdio.h>
const int stepsPerRevolution = 200;
#define pwmA 3
#define pwmB 11
#define brakeA 9
#define brakeB 8
#define dirA 12
#define dirB 13
#define SCL 1
#define SDA 1
int k,i,q,t;
int stepp;
int led=13;
int stopp=1;
Stepper myStepper = Stepper(stepsPerRevolution, dirA, dirB);

void setup() {
  //The set upp nedded for the stepmotor
  pinMode(3, OUTPUT);
  pinMode(pwmA, OUTPUT);
  pinMode(pwmB, OUTPUT);
  pinMode(brakeA, OUTPUT);
  pinMode(brakeB, OUTPUT);
  digitalWrite(pwmA, HIGH);
  digitalWrite(pwmB, HIGH);
  digitalWrite(brakeA, LOW);
  digitalWrite(brakeB, LOW);
  Serial.begin(9600);
  pinMode(led, OUTPUT) ;
  Serial.begin(9600);
 myStepper.setSpeed(60);
}
void loop()
{
```

```
  while(stopp<2) //to make sure the test stopps after 100 test rounds
   {
         for (int k=0; k <= 99; ++k)
          {
            myStepper.step(160); //set the first test point at 8cm

             for ( int i=0; i <= 7; ++i)//set the number of testpoints
              {
                int Value = analogRead(A5); //read the value at every
test point
                float voltage= Value * (5.0 / 1023.0);
                Serial.println(voltage);//print to COM-port
                myStepper.step(400); //move a 1 cm


               }
              stepp=(-3910);
             myStepper.step(stepp);// after all test point are the
card moved upp to start position
           }
       stopp++; //in order to stop the motor after 100 test runs.
 }
}
```

B   Design for the clip on the test bench
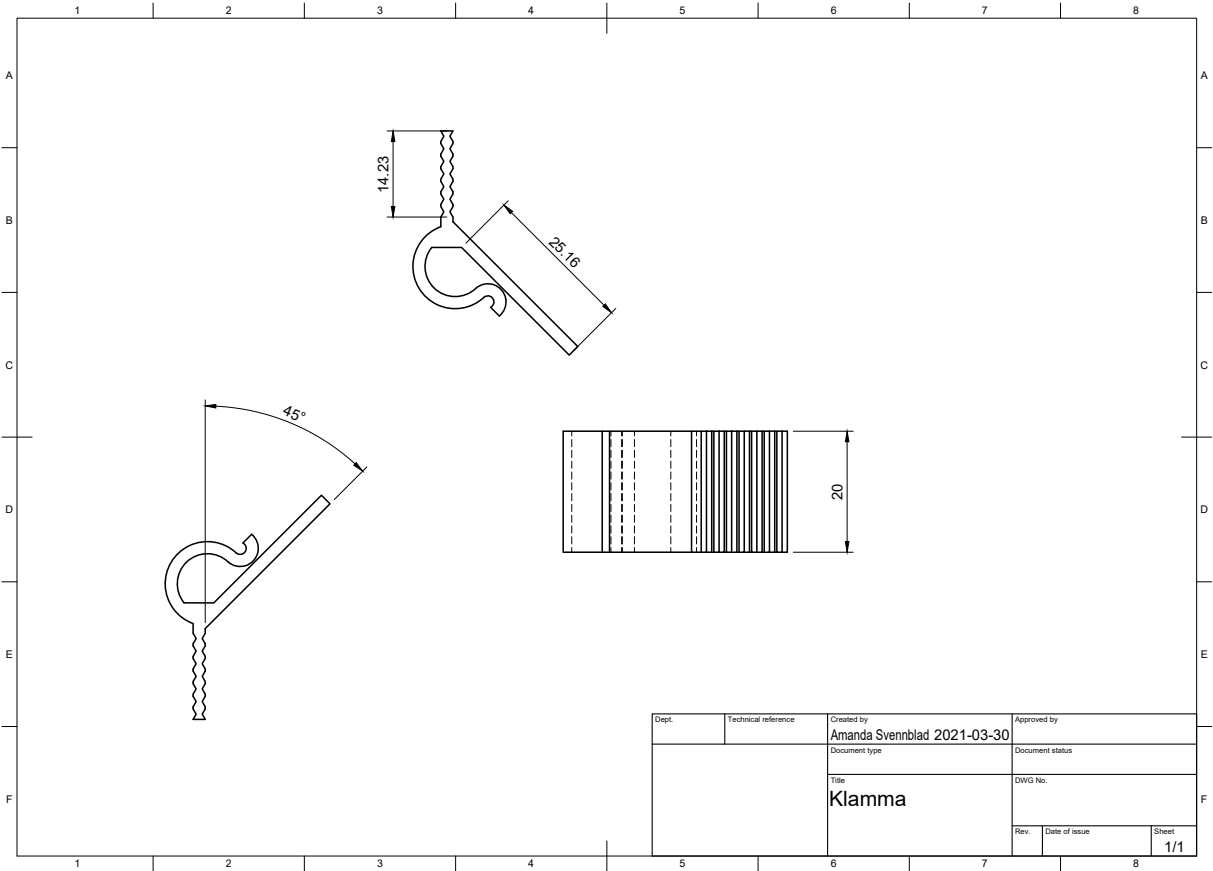
Dept.	Technical reference	Created by		Approved by	
		Amanda Svennblad 2021-03-30			
		Document type		Document status	
		Title		DWG No.	
		Klamma			
				Rev.	Date of issue	Sheet
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C Matlab code for the red board

```matlab
clc
clear all
%test for the red card, pararell setup
%take in the txt with the 100 testresult
test = dlmread('röd_pararell,test,test.txt')'
d=1
%convert the test result to an matrix (with number of tests X testpoints)
for i=1:100

    for k=1:9
        testmatris(i,k)=test(d);
        d=d+1;

    end
end

testmedel=mean(testmatris(:,:)) %take ot the mean value
%the distance for the testpoint used in plotting later
cm=[8 7 6 5 4 3 2 1 0 ];

for i=1:9 %calculate the confidence interval
 x = testmatris(:,i);                            % Create Data
 SEM = std(x)/sqrt(length(x));                   % Standard Error
 ts = tinv([0.025  0.975],length(x)-1);     % T-Score
 CI(i,1) = mean(x) + ts(1)'*SEM;
 CI(i,2) = mean(x) + ts(2)'*SEM;
 err(i) = diff(CI(i,:)) %calculated confidence interval

end
%plott the test meadelvalue with a 95% confidence interval
 ylabel('Vin')
 errorbar(cm,testmedel, err,'r')
 xlabel('cm')

 title('Red, Parallel test')
```

```matlab
%test red card, skin setup.
%The code is written in the same manner as for the pararell set up,
%ok at the pararel setup for comments.
clc
clear all
test = dlmread('röd_skin,test,test.txt')'
d=1
for i=1:100

    for k=1:9
        testmatris(i,k)=test(d);
        d=d+1;

    end
end

testmedel=mean(testmatris(:,:))
cm=[8 7 6 5 4 3 2 1 0 ];

for i=1:9
 x = testmatris(:,i);
 SEM = std(x)/sqrt(length(x));
```

```matlab
ts = tinv([0.025  0.975],length(x)-1);
CI(i,1) = mean(x) + ts(1)'*SEM;
CI(i,2) = mean(x) + ts(2)'*SEM;
err(i) = diff(CI(i,:))

end

errorbar(cm,testmedel, err,'r')
ylabel('Vin')
xlabel('cm')
title('Red, Parallel test with skin ')
```

```matlab
%test red card, angeled setup.
%The code is written in the same manner as for the pararell set up,
%look at the pararel setup for comments.
clc
clear all
test = dlmread('röd_45_grader,test,test.txt')'

d=1
for i=1:100

    for k=1:9
        testmatris(i,k)=test(d);
        d=d+1;

    end
end
testmedel=mean(testmatris(:,:))
cm=[8 7 6 5 4 3 2 1 0 ];

for i=1:9
 x = testmatris(:,i);
 SEM = std(x)/sqrt(length(x));
 ts = tinv([0.025  0.975],length(x)-1);
 CI(i,1) = mean(x) + ts(1)'*SEM;
 CI(i,2) = mean(x) + ts(2)'*SEM;
 err(i) = diff(CI(i,:))
end
 errorbar(cm,testmedel, err,'r')
 ylabel('Vin')
 xlabel('cm')
 title('Red, angled test ')
```

```matlab
%test red card, pork chop setup.
%The code is written in the same manner as for the pararell set up,
%look at the pararel setup for comments.
clc
clear all
test = dlmread('röd_kotlett,test,test.txt')%read in text file
d=1
for i=1:100

    for k=1:7
        testmatris(i,k)=test(d);
        d=d+1;
```

```matlab
        end
end

testmedel=mean(testmatris(:,:))
cm=[8 7 6 5 4 3 2 ];

for i=1:7
 x = testmatris(:,i);
 SEM = std(x)/sqrt(length(x));
 ts = tinv([0.025  0.975],length(x)-1);
 CI(i,1) = mean(x) + ts(1)'*SEM;
 CI(i,2) = mean(x) + ts(2)'*SEM;
 err(i) = diff(CI(i,:))

end
 errorbar(cm,testmedel, err,'r')
 ylabel('Vin')
 xlabel('cm')
 title('Red, Parallel test with pork chop  ')
```

```matlab
%test red card, side by side setup.
%The code is written in the same manner as for the pararell set up,
%look at the pararel setup for comments.
clc
clear all
test = dlmread('röd_sidebyside.txt')
d=1
for i=1:100

    for k=1:8
        testmatris(i,k)=test(d);
        d=d+1;

    end
end

testmedel=mean(testmatris(:,:))
cm=[8 7 6 5 4 3 2 1 ];

for i=1:8
 x = testmatris(:,i);
 SEM = std(x)/sqrt(length(x));
 ts = tinv([0.025  0.975],length(x)-1);
 CI(i,1) = mean(x) + ts(1)'*SEM;
 CI(i,2) = mean(x) + ts(2)'*SEM;
 err(i) = diff(CI(i,:))

end
 errorbar(cm,testmedel, err,'r')
 ylabel('Vin')
 xlabel('cm')
 title('Red, side by side test ')
```

D   Matlab code for the ams board

```matlab
clc
clear all
%test for the Ams card, pararell setup
%take in the txt with the 100 testresult
 test = dlmread('ams_pararell,test,test.txt')


d=1
%convert the test result to an matrix (with number of tests X testpoints)
for i=1:100

    for k=1:9
        testmatris(i,k)=test(d);
        d=d+1;

    end


end

testmedel=mean(testmatris(:,:)) %take ot the mean value
 %the distance for the testpoint used in plotting later
cm=[8 7 6 5 4 3 2 1 0 ];

for i=1:9 %calculate the confidence interval
 x = testmatris(:,i);                          % Create Data
 SEM = std(x)/sqrt(length(x));                 % Standard Error
 ts = tinv([0.025  0.975],length(x)-1);        % T-Score
 CI(i,1) = mean(x) + ts(1)'*SEM;
 CI(i,2) = mean(x) + ts(2)'*SEM;
 err(i) = diff(CI(i,:)) %calculated confidence interval

end


%plott the test meadelvalue with a 95% confidence interval
 errorbar(cm,testmedel, err,'r')
 ylabel('Vin')
 xlabel('cm')
 title('AMS, Parallel test')
```

```matlab
%test Ams card, skin setup.
%The code is written in the same manner as for the pararell set up,
%look at the pararel setup for comments.
 clc
 clear all
 test = dlmread('ams_skin,test,test.txt')
 d=1
for i=1:100

    for k=1:9
        testmatris(i,k)=test(d);
        d=d+1;

    end
end

testmedel=mean(testmatris(:,:))
```

```matlab
cm=[8 7 6 5 4 3 2 1 0 ];

for i=1:9
 x = testmatris(:,i);
 SEM = std(x)/sqrt(length(x));
 ts = tinv([0.025  0.975],length(x)-1);
 CI(i,1) = mean(x) + ts(1)'*SEM;
 CI(i,2) = mean(x) + ts(2)'*SEM;
 err(i) = diff(CI(i,:))
end

 errorbar(cm,testmedel, err,'r')
 ylabel('Vin')
 xlabel('cm')
 title('AMS, Parallel test with skin')
```

```matlab
%test Ams card, angled setup.
%The code is written in the same manner as for the pararell set up,
%look at the pararel setup for comments
clc
clear all
test =dlmread('ams_45grader,test,test.txt')
d=1
for i=1:100

    for k=1:9
        testmatris(i,k)=test(d);
        d=d+1;

    end
end
testmedel=mean(testmatris(:,:))
cm=[8 7 6 5 4 3 2 1 0 ];

for i=1:9
 x = testmatris(:,i);
 SEM = std(x)/sqrt(length(x));
 ts = tinv([0.025  0.975],length(x)-1);
 CI(i,1) = mean(x) + ts(1)'*SEM;
 CI(i,2) = mean(x) + ts(2)'*SEM;
 err(i) = diff(CI(i,:))
end

 errorbar(cm,testmedel, err,'r')
 ylabel('Vin')
 xlabel('cm')
 title('AMS, angled test ')
```

```matlab
%test Ams card, pork chop setup.
%The code is written in the same manner as for the pararell set up,
%look at the pararel setup for comments
clc
clear all
test = dlmread('ams_kotlett,test,test.txt')
d=1
for i=1:100
```

```matlab
    for k=1:7
        testmatris(i,k)=test(d);
        d=d+1;
    end
end
testmedel=mean(testmatris(:,:))
cm=[8 7 6 5 4 3 2 ];

for i=1:7
 x = testmatris(:,i);
 SEM = std(x)/sqrt(length(x));
 ts = tinv([0.025  0.975],length(x)-1);
 CI(i,1) = mean(x) + ts(1)'*SEM;
 CI(i,2) = mean(x) + ts(2)'*SEM;
 err(i) = diff(CI(i,:))

end
 errorbar(cm,testmedel, err,'r')
 ylabel('Vin')
 xlabel('cm')
 title('AMS, Parallel test with pork chop')
```

```matlab
%test Ams card, side by side setup.
%The code is written in the same manner as for the pararell set up,
%look at the pararel setup for comments
clc
clear all
test = dlmread('ams_sidebyside.txt')
d=1
for i=1:100

    for k=1:8
        testmatris(i,k)=test(d);
        d=d+1;

    end
end

testmedel=mean(testmatris(:,:))
cm=[8 7 6 5 4 3 2 1 ];

for i=1:8
 x = testmatris(:,i);
 SEM = std(x)/sqrt(length(x));
 ts = tinv([0.025  0.975],length(x)-1);
 CI(i,1) = mean(x) + ts(1)'*SEM;
 CI(i,2) = mean(x) + ts(2)'*SEM;
 err(i) = diff(CI(i,:))

end
 errorbar(cm,testmedel, err,'r')
 ylabel('Vin')
 xlabel('cm')
 title('AMS, side by side test ')
```

E Matlab code for the Y1 board

```matlab
%Pararella tester Y1 kortet
clc
clear all
test = dlmread('Y1_pararell,test,test.txt')
d=1
%convert the test result to an matrix (with number of tests X testpoints)
for i=1:100
    for k=1:9
        testmatris(i,k)=test(d);
        d=d+1;

    end
end

testmedel=mean(testmatris(:,:)) %take ot the mean value
%the distance for the testpoint used in plotting later
cm=[8 7 6 5 4 3 2 1 0 ];

for i=1:9 %calculate the confidence interval
 x = testmatris(:,i);                       % Create Data
 SEM = std(x)/sqrt(length(x));              % Standard Error
 ts = tinv([0.025  0.975],length(x)-1);     % T-Score
 CI(i,1) = mean(x) + ts(1)'*SEM;
 CI(i,2) = mean(x) + ts(2)'*SEM;
 err(i) = diff(CI(i,:)) %calculated confidence interval

end
%plott the test meadelvalue with a 95% confidence interval
 errorbar(cm,testmedel, err,'r')
 ylabel('Vin')
 xlabel('cm')
 title('Y1, Parallel test')
```

```matlab
 %test Y1 card, skin setup.
 %The code is written in the same manner as for the pararell set up,
 %look at the pararel setup for comments.
 clc
 clear all
 test = dlmread('Y1_skin,test,test.txt')
 d=1
for i=1:100

    for k=1:9
        testmatris(i,k)=test(d);
        d=d+1;

    end
end

testmedel=mean(testmatris(:,:))
cm=[8 7 6 5 4 3 2 1 0 ];

for i=1:9
 x = testmatris(:,i);
 SEM = std(x)/sqrt(length(x));
 ts = tinv([0.025  0.975],length(x)-1);
 CI(i,1) = mean(x) + ts(1)'*SEM;
 CI(i,2) = mean(x) + ts(2)'*SEM;
```

```matlab
  err(i) = diff(CI(i,:))

end

  errorbar(cm,testmedel, err,'r')
  ylabel('Vin')
  xlabel('cm')
  title('Y1, Parallel test with skin')
```

```matlab
%test Y1 card, angled setup.
%The code is written in the same manner as for the pararell set up,
%look at the pararel setup for comments.
  clc
  clear all
  test = dlmread('Y1_45_grader,test,test.txt')
   d=1
for i=1:100

     for k=1:9
         testmatris(i,k)=test(d);
         d=d+1;

     end
end

testmedel=mean(testmatris(:,:))
cm=[8 7 6 5 4 3 2 1 0 ];

for i=1:9
 x = testmatris(:,i);
 SEM = std(x)/sqrt(length(x));
 ts = tinv([0.025  0.975],length(x)-1);
 CI(i,1) = mean(x) + ts(1)'*SEM;
 CI(i,2) = mean(x) + ts(2)'*SEM;
 err(i) = diff(CI(i,:))

end

  errorbar(cm,testmedel, err,'r')
  ylabel('Vin')
  xlabel('cm')
  title('Y1, angled test ')
```

```matlab
  %test Y1 card, pork chop setup.
  %The code is written in the same manner as for the pararell set up,
  %look at the pararel setup for comments.
  clc
  clear all
  test = dlmread('Y1_kotlett,test,test.txt')
  d=1
for i=1:100

     for k=1:9
         testmatris(i,k)=test(d);
         d=d+1;

     end
```

```
end

testmedel=mean(testmatris(:,:))
cm=[8 7 6 5 4 3 2 1 0 ];

for i=1:9
 x = testmatris(:,i);
 SEM = std(x)/sqrt(length(x));
 ts = tinv([0.025  0.975],length(x)-1);
 CI(i,1) = mean(x) + ts(1)'*SEM;
 CI(i,2) = mean(x) + ts(2)'*SEM;
 err(i) = diff(CI(i,:))

end

 errorbar(cm,testmedel, err,'r')
 ylabel('Vin')
 xlabel('cm')
 title('Y1, Parallel test with pork chop')
```

```
%test Y1 card, side by side setup.
%The code is written in the same manner as for the pararell set up,
%look at the pararel setup for comments.
 clc
clear all
test = dlmread('Y1_sidebyside.txt')
d=1
for i=1:100

    for k=1:9
        testmatris(i,k)=test(d);
        d=d+1;

    end
end

testmedel=mean(testmatris(:,:))
cm=[8 7 6 5 4 3 2 1 0 ];

for i=1:9
 x = testmatris(:,i);
 SEM = std(x)/sqrt(length(x));
 ts = tinv([0.025  0.975],length(x)-1);
 CI(i,1) = mean(x) + ts(1)'*SEM;
 CI(i,2) = mean(x) + ts(2)'*SEM;
 err(i) = diff(CI(i,:))

end

 errorbar(cm,testmedel, err,'r')
 ylabel('Vin')
 xlabel('cm')
 title('Y1, side by side test ')
```

F Matlab code for the Y2 board

```matlab
%Pararella tester Y2 kortet
clc
clear all
test = dlmread('Y2_pararell,test,test.txt')
d=1
%convert the test result to an matrix (with number of tests X testpoints)
for i=1:100

    for k=1:9
        testmatris(i,k)=test(d);
        d=d+1;

    end
end

testmedel=mean(testmatris(:,:)) %take ot the mean value
%the distance for the testpoint used in plotting late
cm=[8 7 6 5 4 3 2 1 0 ]; r

for i=1:9 %calculate the confidence interval
 x = testmatris(:,i);                       % Create Data
 SEM = std(x)/sqrt(length(x));              % Standard Error
 ts = tinv([0.025  0.975],length(x)-1);     % T-Score
 CI(i,1) = mean(x) + ts(1)'*SEM;
 CI(i,2) = mean(x) + ts(2)'*SEM;
 err(i) = diff(CI(i,:)) %calculated confidence interval

end
%plott the test meadelvalue with a 95% confidence interval
 errorbar(cm,testmedel, err,'r')
 ylabel('Vin')
 xlabel('cm')
 title('Y2, Parallel test')
```

```matlab
 %test Y2 card, skin setup.
 %The code is written in the same manner as for the pararell set up,
 %look at the pararel setup for comments.
 clc
 clear all
 test = dlmread('Y2_skin,test,test.txt')
 d=1
for i=1:100

    for k=1:9
        testmatris(i,k)=test(d);
        d=d+1;

    end
end

testmedel=mean(testmatris(:,:))
cm=[8 7 6 5 4 3 2 1 0 ];

for i=1:9
 x = testmatris(:,i);
 SEM = std(x)/sqrt(length(x));
 ts = tinv([0.025  0.975],length(x)-1);
 CI(i,1) = mean(x) + ts(1)'*SEM;
```

```
 CI(i,2) = mean(x) + ts(2)'*SEM;
 err(i) = diff(CI(i,:))

end

 errorbar(cm,testmedel, err,'r')
 ylabel('Vin')
 xlabel('cm')
 title('Y2, Parallel test with skin')
```

```
%test Y2 card, angled setup.
%The code is written in the same manner as for the pararell set up,
%look at the pararel setup for comments.
 clc
 clear all
 test = dlmread('Y2_45_grader,test,test.txt')
  d=1
for i=1:100

    for k=1:9
        testmatris(i,k)=test(d);
        d=d+1;

    end
end

testmedel=mean(testmatris(:,:))
cm=[8 7 6 5 4 3 2 1 0 ];

for i=1:9
 x = testmatris(:,i);
 SEM = std(x)/sqrt(length(x));
 ts = tinv([0.025  0.975],length(x)-1);
 CI(i,1) = mean(x) + ts(1)'*SEM;
 CI(i,2) = mean(x) + ts(2)'*SEM;
 err(i) = diff(CI(i,:))

end

 errorbar(cm,testmedel, err,'r')
 ylabel('Vin')
 xlabel('cm')
 title('Y2, angled test ')
```

```
 %test Y2 card, pork chop setup.
 %The code is written in the same manner as for the pararell set up,
 %look at the pararel setup for comments.
 clc
 clear all
 test = dlmread('Y2_kotlett,test,test.txt')
 d=1
for i=1:100

    for k=1:9
        testmatris(i,k)=test(d);
        d=d+1;
```

```matlab
        end
end

testmedel=mean(testmatris(:,:))
cm=[8 7 6 5 4 3 2 1 0 ];

for i=1:9
 x = testmatris(:,i);
 SEM = std(x)/sqrt(length(x));
 ts = tinv([0.025  0.975],length(x)-1);
 CI(i,1) = mean(x) + ts(1)'*SEM;
 CI(i,2) = mean(x) + ts(2)'*SEM;
 err(i) = diff(CI(i,:))

end

 errorbar(cm,testmedel, err,'r')
 ylabel('Vin')
 xlabel('cm')
 title('Y2, Parallel test with pork chop')
```

```matlab
%test Y2 card, side by side setup.
%The code is written in the same manner as for the pararell set up,
%look at the pararel setup for comments.
 clc
clear all
test = dlmread('Y2_sidebyside.txt')
d=1
for i=1:100

    for k=1:9
        testmatris(i,k)=test(d);
        d=d+1;

    end
end

testmedel=mean(testmatris(:,:))
cm=[8 7 6 5 4 3 2 1 0 ];

for i=1:9
 x = testmatris(:,i);
 SEM = std(x)/sqrt(length(x));
 ts = tinv([0.025  0.975],length(x)-1);
 CI(i,1) = mean(x) + ts(1)'*SEM;
 CI(i,2) = mean(x) + ts(2)'*SEM;
 err(i) = diff(CI(i,:))

end

 errorbar(cm,testmedel, err,'r')
 ylabel('Vin')
 xlabel('cm')
 title('Y2, side by side test ')
```

G   Matlab code for comparison between the board

```matlab
%in order to plotted all board in the graphs are the matlab code for all the cards
%the values needed for the plotts colected in the matlab code,
%that where written for each board.
%All the boards values are collected here and then plotted in one grap
clc
clear all
 % values for all the boards at the pararell setup
 %red
err=[ 0.3591    0.1509    0.1091    0.0793    0.0187    0.1297    0.0018    ];
cm=[8 7 6 5 4 3 2 ];
testmedel =[0.6522    1.8959    2.4867    3.0165    3.6906    3.6857    3.7181    ];
hold on
errorbar(cm,testmedel, err,'r')
%ams
err =[0.1250    0.0020    0.0020    0.1260    0.0020    0.1318    0.0152] ;
testmedel =[ 3.5777    3.6280    3.6250    3.5911    3.6259    3.5897    3.6259 ];
cm=[8 7 6 5 4 3 2  ];
hold on
errorbar(cm,testmedel, err,'g')
%Y1
testmedel =[0.4684    0.2955    0.3520    0.4973    0.4250    0.7542    2.5922];
err =[ 0.2938    0.2101    0.2252    0.3039    0.3003    0.3669    0.0914];
cm=[8 7 6 5 4 3 2 ];
hold on
errorbar(cm,testmedel, err,'b')
%Y2
cm=[ 8 7 6 5 4 3 2 ];
err =[0.2328    0.2386    0.3172    0.3295    0.1005    0.1207    0.1423];
testmedel =[0.3398    0.3357    0.6746    0.5839    1.9340    2.9997    3.5379];
hold on
errorbar(cm,testmedel, err,'k')
ylabel('Vin')
xlabel('cm')
title('comparison, parallel test')
legend ('red','ams','Y1','Y2')
```

```matlab
 %This are done in the same manner as for the pararell comparision.
 %skin setup
clc
clear all
% values for all the boards at the pararell setup
 %red
err=[0.3006    0.0059    0.0451    0.0061    0.0299    0.1639    0.0018    ];
cm=[8 7 6 5 4 3 2 ];
testmedel =[0.5473    1.8982    2.4210    2.9853 3.7043 3.6477    3.7174    ];
hold on
errorbar(cm,testmedel, err,'r')
%ams
err =[ 0.1281    0.0253    0.1321    0.1454 0.0178    0.0685    0.1251    ] ;
testmedel =[3.6258    3.6312    3.5967    3.5978 3.6330    3.6220    3.6102    ];
cm=[8 7 6 5 4 3 2  ];
hold on
errorbar(cm,testmedel, err,'g')
%Y1
testmedel =[0.4608    0.3949    0.3817    0.3438 0.5588    0.6456    0.7222    ];
err =[0.3136    0.2552    0.2398    0.2314 0.3299    0.3686    0.3959    ] ;
cm=[8 7 6 5 4 3 2 ];
hold on
```

```matlab
errorbar(cm,testmedel, err,'b')
%Y2
cm=[ 8 7 6 5 4 3 2 ];
err =[0.2636    0.2815    0.3078    0.3534  0.0487    0.1290    0.1350];
testmedel =[ 0.4218    0.4508    0.4868    0.6002 2.2352    3.4037    3.4973];
hold on
errorbar(cm,testmedel, err,'k')
ylabel('Vin')
xlabel('cm')
title('comparison, skin test')
legend ('red','ams','Y1','Y2')
```

```matlab
 %This are done in the same manner as for the pararell comparision.
 %angled setup
clc
clear all
%red
err=[0.2269    0.2951    0.1017    0.0752  0.0681    0.1421    0.0043];
testmedel =[ 0.3538    0.4822    1.7515    2.3966  2.9459    3.6605 3.7044];
cm=[8 7 6 5 4 3 2 ];
hold on
errorbar(cm,testmedel, err,'r')
%ams
err =[  0.0139    0.1145    0.1263    0.125  0.0324    0.1334    0.0016] ;
testmedel =[  2.9671    3.4048    3.5789    3.5871  3.6067    3.5873    3.6217];
cm=[8 7 6 5 4 3 2  ];
hold on
errorbar(cm,testmedel, err,'g')
%Y1
testmedel =[0.6039    0.4325    0.4305    0.4442  0.4766    0.3738    0.7555    ];
err =[ 0.3430    0.2968    0.2480    0.2637  0.3140    0.2975    0.3965   ];
cm=[8 7 6 5 4 3 2 ];
hold on
errorbar(cm,testmedel, err,'b')
%Y2
cm=[ 8 7 6 5 4 3 2 ];
err =[0.1987    0.2150    0.2215    0.2410 0.3030    0.0296    0.0130];
testmedel =[  0.4175    0.3966    0.3549    0.3989  0.5265    2.0565    3.1930];
hold on
errorbar(cm,testmedel, err,'k')
ylabel('Vin')
xlabel('cm')
title('comparison, angled test')
legend ('red','ams','Y1','Y2')
```

```matlab
 %This are done in the same manner as for the pararell comparision.
 %pork chop setup
clc
clear all
err=[ 0.2223    0.3182    0.0363    0.0314 0.0439    0.0021    0.0022];
cm=[8 7 6 5 4 3 2 ];
testmedel =[ 0.3752    0.6454    1.9297    2.4842  3.0348    3.7671    3.7682];
hold on
errorbar(cm,testmedel, err,'r')
%ams
err =[0.0125    0.1374    0.0066    0.1307 0.0018    0.0158    0.0365] ;
testmedel =[3.6483    3.6071    3.6385    3.6052 3.6416    3.6370    3.6514];
```

```matlab
cm=[8 7 6 5 4 3 2  ];
hold on
errorbar(cm,testmedel, err,'g')
%Y1
testmedel =[ 0.3547    0.3912    0.2197    0.4038 0.5036    0.7278    2.6620];
err =[ 0.2102    0.2014    0.1709    0.2699 0.2939    0.3667    0.0370];
cm=[8 7 6 5 4 3 2 ];
hold on
errorbar(cm,testmedel, err,'b')
%Y2
cm=[ 8 7 6 5 4 3 2 ];
err =[ 0.3518    0.3513    0.3686    0.4507 0.1352    0.0253    0.1397];
testmedel =[ 0.5843    0.5069    0.5557    0.9178 2.2158    3.3207    3.4844];
hold on
errorbar(cm,testmedel, err,'k')
ylabel('Vin')
xlabel('cm')
title('comparison, pork chop test')
legend ('red','ams','Y1','Y2')
```

```matlab
 %This are done in the same manner as for the pararell comparision.
 %sidebyside setup
clear all
err=[ 0.0955    0.1106    0.1201    0.1451 0.1178    0.1680    0.3309    0.0518];
cm=[8 7 6 5 4 3 2 1];
testmedel =[0.1423    0.1579    0.1844    0.2508 0.2225    0.2481    0.5640    3.1950];
hold on
errorbar(cm,testmedel, err,'r')
%ams
err =[ 0.1087    0.1718    0.1894    0.1423 0.0543    0.0102    0.0970    0.1275] ;
testmedel =[ 2.2279    2.1342    2.1920    2.2429 1.7970    0.4625    1.9358    3.5032];
cm=[8 7 6 5 4 3 2  1];
hold on
errorbar(cm,testmedel, err,'g')
%Y1
testmedel =[0.3195    0.3302    0.3653    0.3768 0.3500    0.3177    0.4070    0.2747];
err =[ 0.2235    0.2141    0.2201    0.2368 0.2223    0.2168    0.2415    0.1885 ];
cm=[8 7 6 5 4 3 2 1];
hold on
errorbar(cm,testmedel, err,'b')
%Y2
cm=[ 8 7 6 5 4 3 2 1];
err =[ 0.1671    0.1621    0.1444    0.1778 0.1611    0.2070    0.1441    0.2061];
testmedel =[0.2699    0.2146    0.2269    0.3481 0.2207    0.3231    0.2353    0.3316];
hold on
errorbar(cm,testmedel, err,'k')
ylabel('Vin')
xlabel('cm')
title('comparison, side by side test')
legend ('red','ams','Y1','Y2')
```

H Matlab code for the efficiency

```matlab
%Y2 efficency are calculated.
%to be abel to calculate the efficency are the the equation in the theory chapter,
%se section mutual inductance used.
%the efficency are calculated as the coupling factor
%* efficency in the energy harvester.
clc
clear all
%parameters used to in the calculation for the mutual inductance
%and the coulping factor are presented down belove.

nt=3;%number of turns on the TX
nr=9;%number of turns on the RX
my0=1.2566*10^(-6); %magnetic permeability of free space
a=0.046/2;%the TX side lengt
c=0.048/2;%the RX side lengt
b=0.06/2;%the TX side lengt
d=0.048/2;%the RX side lengt
z=0; %the distance beetween the coils are declared as z
ll=0.0000143;%inductance for the RX board
lt=1.91e-6; %inductance for the TX board
%the next two for-loops calculate the mutual inductance,
%the equation can be seen in he theory chapter, se section mutual inductance.
for i=1:11
    z=z+0.01;
    b1(i)=sqrt(((b+d)^2+(a+c)^2+z.^2));
    b2(i)=sqrt(((b+d)^2+(a-c)^2+z.^2));
    b3(i)=sqrt(((b-d)^2+(a-c)^2+z.^2));
    b4(i)=sqrt(((b-d)^2+(a+c)^2+z.^2));
    m1(i)=b1(i)-b2(i);
    m2(i)=b3(i)-b4(i);
    mij_1(i)=m1(i)+m2(i);
    mij_2(i)=(a+c)*(-atanh((a+c)/sqrt(((b+d)^2+(a+c)^2+z^2)))
    +atanh((a+c)/sqrt(((b-d)^2+(a+c)^2+z^2))));
    mij_3(i)=(a-c)*(-atanh((a-c)/sqrt(((b-d)^2+(a-c)^2+z^2)))
    +atanh((a-c)/sqrt(((b+d)^2+(a-c)^2+z^2))));
    mij(i)=((my0)/(2*pi))*(mij_1(i)+mij_2(i)+mij_3(i));
    m_1(i)=mij(i);
end
a=b;
c=d;
b=0.0462/2;
d=0.06/2;
for i=1:11
    z=z+0.01;
    b1(i)=sqrt(((b+d)^2+(a+c)^2+z.^2));
    b2(i)=sqrt(((b+d)^2+(a-c)^2+z.^2));
    b3(i)=sqrt(((b-d)^2+(a-c)^2+z.^2));
    b4(i)=sqrt(((b-d)^2+(a+c)^2+z.^2));
    m1(i)=b1(i)-b2(i);
    m2(i)=b3(i)-b4(i);
    mij_11(i)=m1(i)+m2(i);
    mij_22(i)=(a+c)*(-atanh((a+c)/sqrt(((b+d)^2+(a+c)^2+z^2)))
    +atanh((a+c)/sqrt(((b-d)^2+(a+c)^2+z^2))));
    mij_33(i)=(a-c)*(-atanh((a-c)/sqrt(((b-d)^2+(a-c)^2+z^2)))
    +atanh((a-c)/sqrt(((b+d)^2+(a-c)^2+z^2))));
    mij(i)=((my0)/(2*pi))*(mij_1(i)+mij_2(i)+mij_3(i));
    m_2(i)=mij(i);
end
for i=1:11
```

```matlab
    %mutual inductance calculated used to calculate the coupling factor
    m(i)= nt*nr*2*(m_2(i)+m_1(i));
    %coupling factor calculated
    k(i)=(m(i)/(sqrt(ll*lt)));
    %the efficency calculated 0.945 is the efficency from the energy harvester
    verkningsgrad(i)=k(i)*0.945;
end
cm=0:10;%create plott point from 10-0cm one every cm.
hold on
plot (cm,k)%the efficency are plotted in a graph over diffrent distances
%Y1 board are calculated in the same maner as for the Y2 board
%to se comment on the code look at the Y2 code for the efficency.

%parameters for Y1
nt=3;
nr=7;
my0=1.2566*10^(-6);
a=0.0462;
b=0.06/2;
c=0.052/2;
d=0.023/2;
lt=1.91e-6;
z=0;
ll=0.00000361
for i=1:11
    z=z+0.01;
    b1(i)=sqrt(((b+d)^2+(a+c)^2+z.^2));
    b2(i)=sqrt(((b+d)^2+(a-c)^2+z.^2));
    b3(i)=sqrt(((b-d)^2+(a-c)^2+z.^2));
    b4(i)=sqrt(((b-d)^2+(a+c)^2+z.^2));
    m1(i)=b1(i)-b2(i);
    m2(i)=b3(i)-b4(i);
    mij_1(i)=m1(i)+m2(i);
    mij_2(i)=(a+c)*(-atanh((a+c)/sqrt(((b+d)^2+(a+c)^2+z^2)))
    +atanh((a+c)/sqrt(((b-d)^2+(a+c)^2+z^2))));
    mij_3(i)=(a-c)*(-atanh((a-c)/sqrt(((b-d)^2+(a-c)^2+z^2)))
    +atanh((a-c)/sqrt(((b+d)^2+(a-c)^2+z^2))));
    mij(i)=((my0)/(2*pi))*(mij_1(i)+mij_2(i)+mij_3(i));
    m_1(i)=mij(i);
end
a=b;
c=d;
b=0.0462/2;
d=0.06/2;
for i=1:11
    z=z+0.01;
    b1(i)=sqrt(((b+d)^2+(a+c)^2+z.^2));
    b2(i)=sqrt(((b+d)^2+(a-c)^2+z.^2));
    b3(i)=sqrt(((b-d)^2+(a-c)^2+z.^2));
    b4(i)=sqrt(((b-d)^2+(a+c)^2+z.^2));
    m1(i)=b1(i)-b2(i);
    m2(i)=b3(i)-b4(i);
    mij_11(i)=m1(i)+m2(i);
    mij_22(i)=(a+c)*(-atanh((a+c)/sqrt(((b+d)^2+(a+c)^2+z^2)))
    +atanh((a+c)/sqrt(((b-d)^2+(a+c)^2+z^2))));
    mij_33(i)=(a-c)*(-atanh((a-c)/sqrt(((b-d)^2+(a-c)^2+z^2)))
    +atanh((a-c)/sqrt(((b+d)^2+(a-c)^2+z^2))));
    mij(i)=((my0)/(2*pi))*(mij_1(i)+mij_2(i)+mij_3(i));
    m_2(i)=mij(i);
end
for i=1:11
```

```matlab
    m(i)= nt*nr*2*(m_2(i)+m_1(i));
    k(i)=(m(i)/(sqrt(ll*lt)));
    verkningsgrad(i)=k(i)*0.945;
end
cm=0:10;
hold on
plot (cm,verkningsgrad)
%red board are calculated in the same manner as for the Y2 board,
%to se comment on the code look at the Y2 code for the efficency.

%parameters for red
nt=3;
nr=9;
my0=1.2566*10^(-6);
a=0.0462;
b=0.06/2;
d=0.014/2;
c=0.014/2;
lt=1.91e-6;
z=0;
ll=0.000000358;
for i=1:11
    z=z+0.01;
    b1(i)=sqrt(((b+d)^2+(a+c)^2+z.^2));
    b2(i)=sqrt(((b+d)^2+(a-c)^2+z.^2));
    b3(i)=sqrt(((b-d)^2+(a-c)^2+z.^2));
    b4(i)=sqrt(((b-d)^2+(a+c)^2+z.^2));
    m1(i)=b1(i)-b2(i);
    m2(i)=b3(i)-b4(i);
    mij_1(i)=m1(i)+m2(i);
    mij_2(i)=(a+c)*(-atanh((a+c)/sqrt(((b+d)^2+(a+c)^2+z^2)))
    +atanh((a+c)/sqrt(((b-d)^2+(a+c)^2+z^2))));
    mij_3(i)=(a-c)*(-atanh((a-c)/sqrt(((b-d)^2+(a-c)^2+z^2)))
    +atanh((a-c)/sqrt(((b+d)^2+(a-c)^2+z^2))));
    mij(i)=((my0)/(2*pi))*(mij_1(i)+mij_2(i)+mij_3(i));
    m_1(i)=mij(i);
end
a=b;
c=d;
b=0.0462/2;
d=0.06/2;
for i=1:11
    z=z+0.01;
    b1(i)=sqrt(((b+d)^2+(a+c)^2+z.^2));
    b2(i)=sqrt(((b+d)^2+(a-c)^2+z.^2));
    b3(i)=sqrt(((b-d)^2+(a-c)^2+z.^2));
    b4(i)=sqrt(((b-d)^2+(a+c)^2+z.^2));
    m1(i)=b1(i)-b2(i);
    m2(i)=b3(i)-b4(i);
    mij_11(i)=m1(i)+m2(i);
    mij_22(i)=(a+c)*(-atanh((a+c)/sqrt(((b+d)^2+(a+c)^2+z^2)))
    +atanh((a+c)/sqrt(((b-d)^2+(a+c)^2+z^2))));
    mij_33(i)=(a-c)*(-atanh((a-c)/sqrt(((b-d)^2+(a-c)^2+z^2)))
    +atanh((a-c)/sqrt(((b+d)^2+(a-c)^2+z^2))));
    mij(i)=((my0)/(2*pi))*(mij_1(i)+mij_2(i)+mij_3(i));
    m_2(i)=mij(i);
end
for i=1:11
    m(i)= nt*nr*2*(m_2(i)+m_1(i));
    k(i)=(m(i)/(sqrt(ll*lt)));
    verkningsgrad(i)=k(i)*0.945;
```

```matlab
end
cm=0:10;
hold on
plot (cm,verkningsgrad)
%Ams board are calculated in the same maner as for the Y2 board,
%to se comment on the code look at the Y2 code for the efficency.

%parameters for Ams
nt=3;
nr=4;
my0=1.2566*10^(-6);
a=0.0462;
b=0.06/2;
d=0.07/2;
c=0.041/2;
lt=1.91e-6;
z=0;
ll=0.00000377
for i=1:11
    z=z+0.01;
    b1(i)=sqrt(((b+d)^2+(a+c)^2+z.^2));
    b2(i)=sqrt(((b+d)^2+(a-c)^2+z.^2));
    b3(i)=sqrt(((b-d)^2+(a-c)^2+z.^2));
    b4(i)=sqrt(((b-d)^2+(a+c)^2+z.^2));
    m1(i)=b1(i)-b2(i);
    m2(i)=b3(i)-b4(i);
    mij_1(i)=m1(i)+m2(i);
    mij_2(i)=(a+c)*(-atanh((a+c)/sqrt(((b+d)^2+(a+c)^2+z^2)))
    +atanh((a+c)/sqrt(((b-d)^2+(a+c)^2+z^2))));
    mij_3(i)=(a-c)*(-atanh((a-c)/sqrt(((b-d)^2+(a-c)^2+z^2)))
    +atanh((a-c)/sqrt(((b+d)^2+(a-c)^2+z^2))));
    mij(i)=((my0)/(2*pi))*(mij_1(i)+mij_2(i)+mij_3(i));
    m_1(i)=mij(i);
end
a=b;
c=d;
b=0.0462/2;
d=0.06/2;
for i=1:11
    z=z+0.01;
    b1(i)=sqrt(((b+d)^2+(a+c)^2+z.^2));
    b2(i)=sqrt(((b+d)^2+(a-c)^2+z.^2));
    b3(i)=sqrt(((b-d)^2+(a-c)^2+z.^2));
    b4(i)=sqrt(((b-d)^2+(a+c)^2+z.^2));
    m1(i)=b1(i)-b2(i);
    m2(i)=b3(i)-b4(i);
    mij_11(i)=m1(i)+m2(i);
    mij_22(i)=(a+c)*(-atanh((a+c)/sqrt(((b+d)^2+(a+c)^2+z^2)))
    +atanh((a+c)/sqrt(((b-d)^2+(a+c)^2+z^2))));
    mij_33(i)=(a-c)*(-atanh((a-c)/sqrt(((b-d)^2+(a-c)^2+z^2)))
    +atanh((a-c)/sqrt(((b+d)^2+(a-c)^2+z^2))));
    mij(i)=((my0)/(2*pi))*(mij_1(i)+mij_2(i)+mij_3(i));
    m_2(i)=mij(i);
end
for i=1:11
   m(i)= nt*nr*2*(m_2(i)+m_1(i));
   k(i)=(m(i)/(sqrt(ll*lt)));
   verkningsgrad(i)=k(i)*0.945;
end
cm=0:10;
hold on
```

```matlab
plot (cm,verkningsgrad)
%ledgens for the graph are determined here
legend('Y2','Y1','red','AMS')
xlabel('Distance in cm')
ylabel('\eta', 'FontSize',20,'FontWeight','bold')
title('\eta for all the diffrent boards')
```

I Matlab code for Psender

```matlab
clc
clear all
%parameters that are needed to calculate the Psender,
%parameters are from board 1 and 5. thise parameter can be seen in the result section
nt=3;
nr=7;
my0=1.2566*10^(-6);
a=0.0462;
b=0.06/2;
c=0.052/2;
d=0.023/2;
lt=1.91e-6;
z=0;
ll=0.00000361;
R=20000000;
I_konst=0.001;
%Psender at the constant current, the value of the current are chosen here
%the equation for  p_sender(i)=((k(i)*0.945)/(R*I_konst^2))^-1,
%to calculte the K(i)=coupling factor are the mutual inductance calculated
%next two for-loops are used to calculate the mutual inductance,
%the equation can be seen in the theory chapter, se section mutual inductance.
for i=1:11
    z=z+0.01;
    b1(i)=sqrt(((b+d)^2+(a+c)^2+z.^2));
    b2(i)=sqrt(((b+d)^2+(a-c)^2+z.^2));
    b3(i)=sqrt(((b-d)^2+(a-c)^2+z.^2));
    b4(i)=sqrt(((b-d)^2+(a+c)^2+z.^2));
    m1(i)=b1(i)-b2(i);
    m2(i)=b3(i)-b4(i);
    mij_1(i)=m1(i)+m2(i);
    mij_2(i)=(a+c)*(-atanh((a+c)/sqrt(((b+d)^2+(a+c)^2+z^2)))
    +atanh((a+c)/sqrt(((b-d)^2+(a+c)^2+z^2))));
    mij_3(i)=(a-c)*(-atanh((a-c)/sqrt(((b-d)^2+(a-c)^2+z^2)))
    +atanh((a-c)/sqrt(((b+d)^2+(a-c)^2+z^2))));

     mij(i)=((my0)/(2*pi))*(mij_1(i)+mij_2(i)+mij_3(i));
     m_1(i)=mij(i);
end
a=b;
c=d;
b=0.0462/2;
d=0.06/2;
for i=1:11
    z=z+0.01;
    b1(i)=sqrt(((b+d)^2+(a+c)^2+z.^2));
    b2(i)=sqrt(((b+d)^2+(a-c)^2+z.^2));
    b3(i)=sqrt(((b-d)^2+(a-c)^2+z.^2));
    b4(i)=sqrt(((b-d)^2+(a+c)^2+z.^2));
    m1(i)=b1(i)-b2(i);
    m2(i)=b3(i)-b4(i);
    mij_11(i)=m1(i)+m2(i);
    mij_22(i)=(a+c)*(-atanh((a+c)/sqrt(((b+d)^2+(a+c)^2+z^2)))
    +atanh((a+c)/sqrt(((b-d)^2+(a+c)^2+z^2))));
    mij_33(i)=(a-c)*(-atanh((a-c)/sqrt(((b-d)^2+(a-c)^2+z^2)))
    +atanh((a-c)/sqrt(((b+d)^2+(a-c)^2+z^2))));
    mij(i)=((my0)/(2*pi))*(mij_1(i)+mij_2(i)+mij_3(i));
    m_2(i)=mij(i);

end
```

```matlab
for i=1:11
    %the equation can be seen in the theory chapter, se section mutual inductance
    m(i)= nt*nr*2*(m_2(i)+m_1(i)); %mutal inductance
    k(i)=(m(i)/(sqrt(ll*lt)));
    p_sender(i)=((k(i)*0.945)/(R*I_konst^2))^-1; %psender is calculated
end
cm=0:10; %create plott point from 10-0cm one every cm.
plot (cm,p_sender)
legend('Psender')
xlabel('Distance in cm')
ylabel('W', 'FontSize',20,'FontWeight','bold')
%plotted the Psender
```

J Matlab code for the efficiency for different sizes on the Y2 board

```matlab
%the code is written in the same way as for the effiency calculation,
%se the appendix for the calculation of the efficency.

%efficency calculation for the Y2board
clc
clear all
nt=3;
nr=9;
my0=1.2566*10^(-6);
a=0.046/2;
c=0.050/2;
b=0.06/2;
d=0.050/2;
z=0;
ll=0.0000169;
lt=1.91e-6;
for i=1:11
    z=z+0.01;
    b1(i)=sqrt(((b+d)^2+(a+c)^2+z.^2));
    b2(i)=sqrt(((b+d)^2+(a-c)^2+z.^2));
    b3(i)=sqrt(((b-d)^2+(a-c)^2+z.^2));
    b4(i)=sqrt(((b-d)^2+(a+c)^2+z.^2));
    m1(i)=b1(i)-b2(i);
    m2(i)=b3(i)-b4(i);
    mij_1(i)=m1(i)+m2(i);
    mij_2(i)=(a+c)*(-atanh((a+c)/sqrt(((b+d)^2+(a+c)^2+z^2)))
    +atanh((a+c)/sqrt(((b-d)^2+(a+c)^2+z^2))));
    mij_3(i)=(a-c)*(-atanh((a-c)/sqrt(((b-d)^2+(a-c)^2+z^2)))
    +atanh((a-c)/sqrt(((b+d)^2+(a-c)^2+z^2))));
    mij(i)=((my0)/(2*pi))*(mij_1(i)+mij_2(i)+mij_3(i));
    m_1(i)=mij(i);
end
a=b;
c=d;
b=0.0462/2;
d=0.06/2;
for i=1:11
    z=z+0.01;
    b1(i)=sqrt(((b+d)^2+(a+c)^2+z.^2));
    b2(i)=sqrt(((b+d)^2+(a-c)^2+z.^2));
    b3(i)=sqrt(((b-d)^2+(a-c)^2+z.^2));
    b4(i)=sqrt(((b-d)^2+(a+c)^2+z.^2));
    m1(i)=b1(i)-b2(i);
    m2(i)=b3(i)-b4(i);
    mij_11(i)=m1(i)+m2(i);
    mij_22(i)=(a+c)*(-atanh((a+c)/sqrt(((b+d)^2+(a+c)^2+z^2)))
    +atanh((a+c)/sqrt(((b-d)^2+(a+c)^2+z^2))));
    mij_33(i)=(a-c)*(-atanh((a-c)/sqrt(((b-d)^2+(a-c)^2+z^2))
    )+atanh((a-c)/sqrt(((b+d)^2+(a-c)^2+z^2))));
    mij(i)=((my0)/(2*pi))*(mij_1(i)+mij_2(i)+mij_3(i));
    m_2(i)=mij(i);
end
for i=1:11
    m(i)= nt*nr*2*(m_2(i)+m_1(i));
    k(i)=(m(i)/(sqrt(ll*lt)));
    verkningsgrad(i)=k(i)*0.945;
end
i=0:10;
hold on
```

```matlab
    plot (i,verkningsgrad);
%Y2 board efficency calculated when y2 board has the same size as the TX
nt=3;
nr=9;
my0=1.2566*10^(-6);
a=0.046/2;
c=a;
b=0.06/2;
d=b;
z=0;
ll=0.0000181; %inductance calculate for the new measurment
lt=1.91e-6;
for i=1:11
    z=z+0.01;
    b1(i)=sqrt(((b+d)^2+(a+c)^2+z.^2));
    b2(i)=sqrt(((b+d)^2+(a-c)^2+z.^2));
    b3(i)=sqrt(((b-d)^2+(a-c)^2+z.^2));
    b4(i)=sqrt(((b-d)^2+(a+c)^2+z.^2));
    m1(i)=b1(i)-b2(i);
    m2(i)=b3(i)-b4(i);
    mij_1(i)=m1(i)+m2(i);
    mij_2(i)=(a+c)*(-atanh((a+c)/sqrt(((b+d)^2+(a+c)^2+z^2)))
    +atanh((a+c)/sqrt(((b-d)^2+(a+c)^2+z^2))));
    mij_3(i)=(a-c)*(-atanh((a-c)/sqrt(((b-d)^2+(a-c)^2+z^2)))
    +atanh((a-c)/sqrt(((b+d)^2+(a-c)^2+z^2))));
    mij(i)=((my0)/(2*pi))*(mij_1(i)+mij_2(i)+mij_3(i));
    m_1(i)=mij(i);
end
a=b;
c=d;
b=0.046/2;
d=0.06/2;
for i=1:11
    z=z+0.01;
    b1(i)=sqrt(((b+d)^2+(a+c)^2+z.^2));
    b2(i)=sqrt(((b+d)^2+(a-c)^2+z.^2));
    b3(i)=sqrt(((b-d)^2+(a-c)^2+z.^2));
    b4(i)=sqrt(((b-d)^2+(a+c)^2+z.^2));
    m1(i)=b1(i)-b2(i);
    m2(i)=b3(i)-b4(i);
    mij_11(i)=m1(i)+m2(i);
    mij_22(i)=(a+c)*(-atanh((a+c)/sqrt(((b+d)^2+(a+c)^2+z^2)))
    +atanh((a+c)/sqrt(((b-d)^2+(a+c)^2+z^2))));
    mij_33(i)=(a-c)*(-atanh((a-c)/sqrt(((b-d)^2+(a-c)^2+z^2)))
    +atanh((a-c)/sqrt(((b+d)^2+(a-c)^2+z^2))));
    mij(i)=((my0)/(2*pi))*(mij_1(i)+mij_2(i)+mij_3(i));
    m_2(i)=mij(i);
end

for i=1:11
   m(i)= nt*nr*2*(m_2(i)+m_1(i));
   k(i)=(m(i)/(sqrt(ll*lt)));
   verkningsgrad(i)=k(i)*0.945;
end
i=0:10;
hold on
plot (i,verkningsgrad);
%Y2 board efficency calculated when y2 board has the same size as the 2*TX
nt=3;
nr=9;
my0=1.2566*10^(-6);
```

```matlab
a=0.046/2;
c=2*a;
b=0.06/2;
d=2*b;
z=0;
ll=0.0000409;%inductance calculate for the new measurment
lt=1.91e-6;
for i=1:11
    z=z+0.01;
    b1(i)=sqrt(((b+d)^2+(a+c)^2+z.^2));
    b2(i)=sqrt(((b+d)^2+(a-c)^2+z.^2));
    b3(i)=sqrt(((b-d)^2+(a-c)^2+z.^2));
    b4(i)=sqrt(((b-d)^2+(a+c)^2+z.^2));
    m1(i)=b1(i)-b2(i);
    m2(i)=b3(i)-b4(i);
    mij_1(i)=m1(i)+m2(i);
    mij_2(i)=(a+c)*(-atanh((a+c)/sqrt(((b+d)^2+(a+c)^2+z^2)))
    +atanh((a+c)/sqrt(((b-d)^2+(a+c)^2+z^2))));
    mij_3(i)=(a-c)*(-atanh((a-c)/sqrt(((b-d)^2+(a-c)^2+z^2)))
    +atanh((a-c)/sqrt(((b+d)^2+(a-c)^2+z^2))));
    mij(i)=((my0)/(2*pi))*(mij_1(i)+mij_2(i)+mij_3(i));
    m_1(i)=mij(i);
 end
 a=b;
 c=d;
 b=0.0462;
 d=0.06;
for i=1:11
    z=z+0.01;
    b1(i)=sqrt(((b+d)^2+(a+c)^2+z.^2));
    b2(i)=sqrt(((b+d)^2+(a-c)^2+z.^2));
    b3(i)=sqrt(((b-d)^2+(a-c)^2+z.^2));
    b4(i)=sqrt(((b-d)^2+(a+c)^2+z.^2));
    m1(i)=b1(i)-b2(i);
    m2(i)=b3(i)-b4(i);
    mij_11(i)=m1(i)+m2(i);
    mij_22(i)=(a+c)*(-atanh((a+c)/sqrt(((b+d)^2+(a+c)^2+z^2)))
    +atanh((a+c)/sqrt(((b-d)^2+(a+c)^2+z^2))));
    mij_33(i)=(a-c)*(-atanh((a-c)/sqrt(((b-d)^2+(a-c)^2+z^2)))
    +atanh((a-c)/sqrt(((b+d)^2+(a-c)^2+z^2))));
    mij(i)=((my0)/(2*pi))*(mij_1(i)+mij_2(i)+mij_3(i));
    m_2(i)=mij(i);
end
for i=1:11
   m(i)= nt*nr*2*(m_2(i)+m_1(i));
   k(i)=(m(i)/(sqrt(ll*lt)));
   verkningsgrad(i)=k(i)*0.945;
end
i=0:10;
hold on
plot (i,verkningsgrad);
%the diffrent sixe of board Y2 are plotted in one graph
xlabel('Distance in cm')
ylabel('\eta', 'FontSize',20,'FontWeight','bold')
legend('Y2','Y2,sized as TX board', 'Y2,sized as 2*TX board')
```

K   Python code for function generator and Arduino

"""Install VISA from RS. download drivers, pip-install"""

```python
import time
from RsInstrument import *
import numpy as np
import pyfirmata


class hm2525():

    #setup for the function generator
    def __init__(self, port="ASRL4:INSTR", verbose=True):
        instr_list = RsInstrument.list_resources('?*', 'rs')
        if verbose:
            print(instr_list)
        # connect
        self.instr = RsInstrument(instr_list[1])

    def amp(self, amp=1):
        self.instr.write_str(f'VOLTAGE {amp}')
        time.sleep(0.1)
        volt = self.instr.query_str('VOLTAGE?')
        return volt

    def freq(self, freq=13.56e6):
        self.instr.write_str(f'FREQUENCY {freq}')
        time.sleep(0.1)
        frek = self.instr.query_str('FREQUENCY?')
        return frek

    def on(self):
        self.instr.write_str(f'OUTPut ON')

    def off(self):
        self.instr.write_str(f'OUTPUT OFF')

    def sine(self, amp=10, offset=0, freq=13.56e6):
        self.instr.write_str("FUNC SIN")
        self.amp(amp=amp)
        self.freq(freq=freq)
        self.on()

    def close(self):
        self.instr.close()

    def id(self):
        a = self.instr.query_str('*IDN?')
        return a

def main():

    arb = hm2525()
    start_voltage = 5
```

```python
    arb.sine(amp=start_voltage, offset=0, freq=13.56e6)

    #connecting the Arduino
    board = pyfirmata.Arduino('COM4')
    it = pyfirmata.util.Iterator(board)
    it.start()

    tvl = board.get_pin('a:5:i')

    #Get the led:s from the board
    led_y = board.get_pin('d:9:p') #yellow led
    led_g = board.get_pin('d:10:p') #green led
    led_r = board.get_pin('d:11:p') #red led

    #Need to wait before reading the analog pin,
    #otherwise the value on the pin is a Nonetype
    time.sleep(2)
    #Analog pin gives value between 0-1,
    #the arduino has a voltage between 0-5 which need to be compensated for.
    value = tvl.read()*5

    low_bound = 1
    high_bound = 3
    step = 0.25

    #Check the value of the analog pin and light the appropirate led
    while True:
        value = tvl.read()*5
        if value <= low_bound:
            led_y.write(1)
            led_r.write(0)
            led_g.write(0)
            arb.amp(start_voltage + step)
            start_voltage = start_voltage + step
            print(value)
        elif value > high_bound:
            led_y.write(0)
            led_r.write(1)
            led_g.write(0)
            arb.amp(start_voltage - step)
            start_voltage = start_voltage - step
            print(value)
        else:
            led_y.write(0)
            led_r.write(0)
            led_g.write(1)
            print(value)

    arb.close()
    it.close()
if __name__ == "__main__":
    main()
```

L   Python code for the transmitter card

```python
import serial
from adafruit_pn532.i2c import PN532_I2C
import board
import busio


i2c = busio.I2C(board.SCL, board.SDA)


pn532 = PN532_I2C(i2c, debug=False)

ic, ver, rev, support = pn532.firmware_version
print("Found PN532 with firmware version: {0}.{1}".format(ver, rev))


pn532.SAM_configuration()

print("Waiting for RFID/NFC card...")
while True:
    # Check if a card is available to read
    uid = pn532.read_passive_target(timeout=0.5)
    print(".", end="")
    # Try again if no card is available.
    if uid is None:
        continue
    print("Found card with UID:", [hex(i) for i in uid])
```