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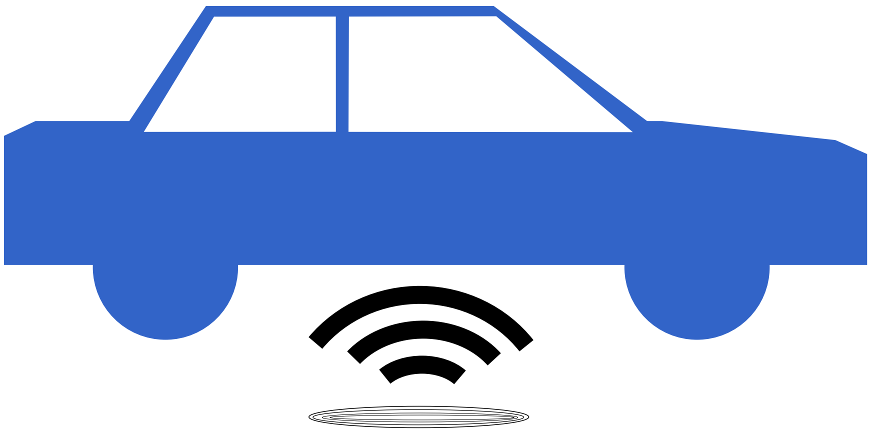

Detection of Foreign Objects

in close proximity to an inductive charger

Master's thesis in Master Programme *Systems, Control and Mechatronics*

PATRIC STRANDBERG
KARL TAGEMAN

Department of Signals and Systems
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016

Master's thesis 2016:EX070/2016

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PATRIC STRANDBERG
KARL TAGEMAN

Supervisor: CHRISTIAN EKMAN, QRTECH
Examiner: TOMAS MCKELVEY, Signals and Systems

Master's Thesis 2016:EX070/2016
Department of Signals and Systems
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

# Abstract

A prototype of a detection unit has been developed, constructed and evaluated. It is capable of detecting live beings, as well as conductive objects. The area of application is together with an inductive charger and its purpose is to detect if live beings or conductive objects are too close to the inductive charger. The detection unit consists of two subsystems, one for each type of object. For live beings, ultrasonic sensors are used and for conductive objects search coil sensors. The system is operational and can detect live beings down to a width of approximately 10 cm and conductive objects the size of a coin.

Keywords: Inductive Charging, Metal Detector, Search Coil Sensor, Magnetic Fields, Ultrasonic Sensors

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Patric & Karl
Gothenburg, Sweden 2016

Contents

1

Introduction

This chapter covers the introduction of this project.

1.1 Background

Wireless, or inductive charging, will be an important technology to facilitate a mass-adoption of electric vehicles. Wireless charging is easier to use compared to its counterpart - a power cord [1]. A wireless charging station can be installed in a garage and the driver can simply park on top of the charging pad to initiate charging. It is also possible for the technology to be implemented in roads, allowing the car to be charged while driving, effectively giving you unlimited range [2].

The batteries in electric vehicles have a very large capacity. To charge these at a reasonable rate, a large amount of power have to be transferred in a short amount of time. The strength of the magnetic field used is proportional to the transferred power. This means that the magnetic field used for charging will be strong. To achieve high efficiency, the field used will also have a high-frequency. A magnetic field with these properties can be hazardous if unwanted conductive objects enter the field as eddy currents will be induced in the objects. Highly conductive objects, such as metallic objects, will be rapidly heated. This can cause both injury and material damage. In living beings the effect of the charging field will cause currents along nerves which can cause muscle spasms and, if the field is strong enough, even nerve damage. According to the International Commission on Non-Ionizing Radiation guidelines [3] the limit for general public exposure to magnetic fields is 6.25 μT in the frequency range $3-150kHz$. This will be surpassed by the field generated by the charger.

It it is not feasible to fence in the dangerous space. Instead, detecting unwanted objects entering the field, and then temporarily turning the field off, is a possible way to make sure that inductive charging is safe.

1.2 Purpose

The purpose was to design and construct a prototype of a detection unit. It should be capable of detecting conductive objects and live beings while in proximity to an alternating high-strength magnetic field. The detection unit should also be able to inform the user and alert the charging station if an object has been detected.

1.3 Problem Formulation

The main problem of this project was to design and construct a detection unit capable of detecting both live beings and conductive objects in a high frequency magnetic field. Detecting live beings and conductive objects were considered as two different problems which required different types of sensors. The electronics should be able to function in proximity to the charging station.

1.3.1 Requirement Specification

The requirement specification for a final version of the detection unit is listed below. Since the charging system that this project work with was incomplete, the specification is based on preliminary information given by the designers of the charging station.

- Live beings equal or larger in size to a fist should be detected
- The area of detection of living beings should be a square with length equal to the inner width of a typical wheel-pair, approximately $1.3m$.
- Conductive objects should be detected before they are within the area where dangerous heating can occur; i.e. between the sender and receiver coil of the charging system.
- Conductive object equal or larger in size to a one SEK coin should be detected
- The detection unit should be able to send a start/stop signal to the charging station
- The detection unit should alert the user when charging has been stopped

1.4 Scope

The detection unit is constructed for use in a laboratory environment. This means that the device is not going to be designed to be weather-resistant, or to survive being run over by a car. It will be tested together with the charging station although not at full capacity. Since this project will only develop a prototype of the detection unit it is not required to cover the entire area in the specification. The requirement concerning sizes and communication should still be fulfilled by the prototype in the covered area. It should also be possible to extend the detection technologies used in the prototype to cover the entire area.

The project will assume to have access to a dc source with desired voltage. In the prototype this will be supplied through a dc power supply.

1.5 Method

A literature study was first carried out in order to get familiar with the topic and current technologies. Different sensor technologies that already exists or can be applied was then evaluated using pros and cons in order to determine suitable ways of detecting live beings as well as conductive objects. The needed electronics was designed and simulated using LTSpice, a software capable of simulating electric circuits. The circuits was simultaneously verified and modified using prototypes in a trial and error fashion before the final version was constructed. The circuit board containing all the electronics was created using Altium Designer. A microcontroller unit (MCU) was used to control the system and all its sensors. It was used to monitor the sensor readings and if a detection was reported communicate this to the charging station and user. The software was written using the Arduino API, which is based on C code but has many built-in libraries and functions which made the embedded programming more simple.

2

Theory

This chapter will list existing theory relevant to this master thesis.

2.1 Exposure to time-varying magnetic fields

Exposure to magnetic fields affect different kinds of materials differently depending on a number of factors. Among these are the frequency of the magnetic field and the conductivity and permeability of the material. This section will differentiate between the effects caused to live beings and conductive objects.

2.1.1 Live Beings

Live beings have small amounts of currents running through them that occur naturally as part of functions within the body. One well-known example is nerve signals which consist of small electrical impulses, but most biochemical reactions uses charged particles in their functions [9]. A low frequency (LF) field, which is the designation for fields in the range of $30kHz - 300kHz$, influence these charged particles through induced currents. A strong magnetic field implies a high induced current. If this current is strong enough, it is possible for it to stimulate nerves and muscles, and disturb other processes in the body as well [9]. Another problem is energy absorption. All materials that are electrically conductive, (which includes live beings) absorbs energy in the form of heat when exposed to alternating magnetic fields. For live beings this generally requires frequencies above $100kHz$. The International Commission On Non-Ionizing Radiation Protection, (ICNIRP) has published guidelines concerning general public exposure to magnetic fields. Between 3kHz and 150kHz, the exposure limits is 6.25 μT [3].

2.1.2 Conductive Objects

Conductive objects exposed to an alternating magnetic field will be subject to a process called induction heating. When the field flows through a conductive material, eddy currents will be induced due to Faraday's law

$$\epsilon = -\frac{d\Phi_B}{dt} \tag{2.1}$$

where ϵ is induced voltage and $\frac{d\Phi_B}{dt}$ the rate of change in magnetic flux. Because of the resistivity in conductive objects the eddy currents will generate heat according to Joule's first law

$$H \propto RI^2t \tag{2.2}$$

This relationship states that the amount of heat generated is proportional to the resistance of the conductor, the current squared and the time. The magnitude of the induced eddy currents depends on several factors. Among these are the strength of the magnetic field itself as well as the frequency of the drive current. Object size, form and material will also affect the current. Magnetic materials such as steel is particularly susceptible to inductive heating. The alternating magnetic field causes the magnetic dipoles of these materials to oscillate. This oscillation creates friction which causes additional heating to occur, [5], [6].

Conductive objects will also affect the magnetic field and make it weaker or stronger, locally, depending on material. Eddy currents induced in conductive objects creates secondary magnetic fields which will work in opposite direction from the original field resulting in a net magnetic field weaker than before. Conductive objects containing ferromagnetic materials such as iron will behave as an inductor core which increases inductance and creates a stronger magnetic field.

The definition of self inductance for a coil is described by

$$L = \frac{N\Phi}{I} \tag{2.3}$$

where N is number of turns, Φ is magnetic flux and I is current. Thus, a change in the magnetic field will change the inductance of the coil exposed the field.

2.2 Resonance

Consider a simple RLC-circuit in a series or parallel configuration as shown in Fig 2.1 and 2.2. They consist of a resistor R, a capacitance C and an inductor L.

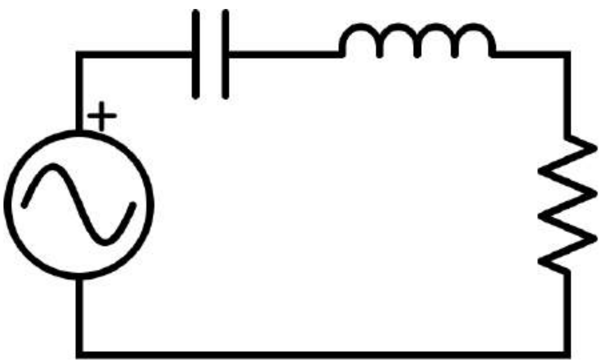

Figure 2.1: Series RLC circuit

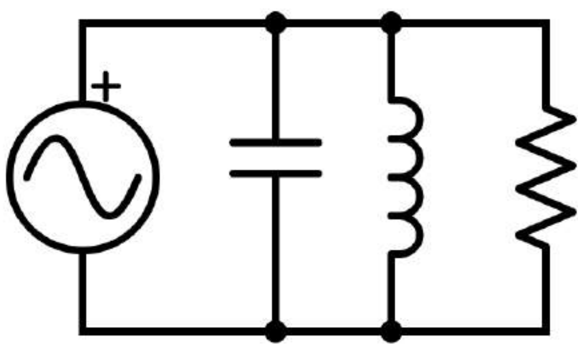

Figure 2.2: Parallel RLC circuit

The impedance of these circuits are

$$Z_S = Z_R + Z_C + Z_L = R + \frac{1}{j\omega C} + j\omega L \tag{2.4}$$

for the series circuit and

$$\frac{1}{Z_P} = \frac{1}{Z_R} + \frac{1}{Z_C} + \frac{1}{Z_L} = \frac{1}{R} + j\omega C + \frac{1}{j\omega L} \tag{2.5}$$

for the parallel circuit. Equation 2.4 and 2.5 can be rearranged as a real and an imaginary part.

$$Z_S = R + j\frac{\omega^2 LC - 1}{\omega C} \tag{2.6}$$

and

$$Z_P = \frac{\omega^2 C^2 R}{1 - 2\omega^2 CL + \omega^4 C^2 L^2 + \omega^2 C^2} + j\frac{\omega CR - \omega^3 C^2 LR}{1 - 2\omega^2 CL + \omega^4 C^2 L^2 + \omega^2 C^2} \tag{2.7}$$

At a certain frequency the imaginary parts in Eq. 2.6 and 2.7 becomes zero and for both configurations this happens when $\omega = \frac{1}{\sqrt{LC}}$. This frequency is called the resonance frequency and denoted ω_0, and is related to the inductance and capacitance by

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{2.8}$$

When in resonance the LC part of the circuit acts as a short circuit for the series configuration and as an open circuit for the parallel configuration. Therefore, the impedance simplifies to

$$Z_S = Z_P = R \tag{2.9}$$

Ohm's law described by Eq. 2.10 gives the relationship between the input voltage, the system impedance, and the current.

$$V = Z \cdot I \tag{2.10}$$

With the impedance minimized at the resonance frequency the current will be maximized. The magnitude of the current depending on the frequency is shown in Fig. 2.3

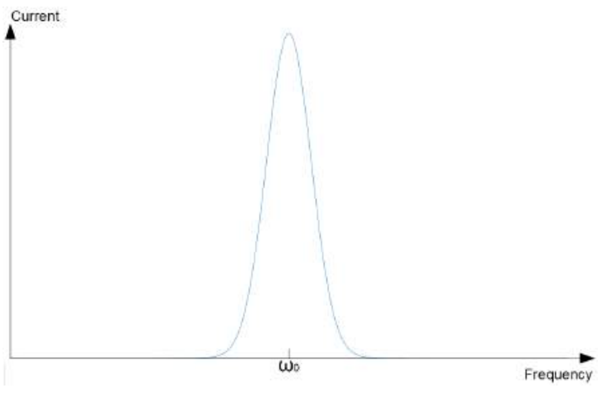

Figure 2.3: Current magnitude

2.2.1 Quality Factor

The quality factor, or Q factor, of a circuit is the ratio between how much energy is stored in the reactive components of the circuit, compared to how much is lost in the resistive ones and can be related to the frequency response in Fig. 2.3. A large Q factor mean that more energy is stored in the LC circuit (less dampened), which results in a higher current magnitude. However the Q factor is also dependent on the bandwidth, i.e how far off from the resonance frequency the circuit can be before the magnitude has decreased with 3dB from the peak value. A large Q factor will result in a large amplification but is harder to tune since smaller deviations from the resonance frequency results in a larger drop in the current magnitude. In the same way a small Q factor will give a smaller amplification but instead making it more robust to changes in frequency. The effect of different Q factors can be seen in Fig. 2.4.

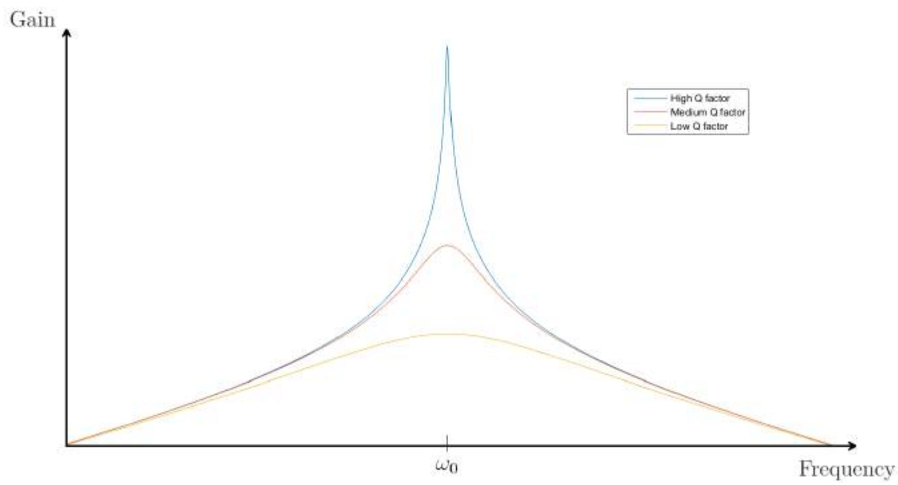

Figure 2.4: Effect of different Q factors

The Q factor is given by

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} \tag{2.11}$$

This shows that the Q factor can be affected just by changing the resistance of the circuit.

3
Choice of Sensor Technologies

Several methods for detecting conductive objects and detecting live beings already exists for many applications. Pros and cons of using these different methods in the limited space under a car will be evaluated in this chapter. According to the requirement specification, live beings larger or equal in size to a hedgehog should be detected while conductive objects the size of a coin and larger should be detected. It is desirable to avoid false positives. However, it is more important to eliminate false negatives. For example, there should under no circumstances be a large living being under the car while the charging is in progress. If the same sensor was to be used for detection of both live beings and conductive objects, one would expect a large amount of false positives. This is because sensors that can detect both would be unable to distinguish between small conductive objects and other kinds of small objects. Therefore a decision was made to use two different kinds of sensors, one for live beings and one for conductive objects.

3.1 Detection of Live Beings

The following methods were considered to use for detection of live beings.

- Motion detectors (Passive infrared (PIR) and ultrasound)
- IR heat sensor or cameras
- Camera and image analysis
- Ultrasonic distance sensors
- Ultrasonic tripwires

Ultrasonic motion detectors work by sending out an ultrasonic pulse and then measuring the frequency of the echo. The Doppler effect will cause the frequency of the response to increase if the detected object was moving towards the sensor, or decrease if the object was moving away. PIR sensors work by measuring the amount of infrared radiation that is hitting the sensor. If this amount changes between one time instance and the next, the sensor knows that an object has moved. A downside of motion detectors is that they can not differentiate between an object leaving the area of detection and an object that has simply stopped moving. This means that motion sensors can not be used to detect the absence of live beings. Therefore, it cannot be used to automatically restart the charging process when a live being has left the dangerous space.

IR heat sensors sense the temperature of objects by detecting how much infrared light they emit. Since the temperature of live beings usually differ from the ground's, this could be used to detect them. One downside is that the sensor has to be placed close to the ground, and asphalt can be rather hot in summer. This could make it difficult to detect live beings as the temperature gap between the live being and the ground might not be large enough that the sensor can differentiate between them. Another downside is that a sufficiently thick shielding object can block the sensor.

Using a camera in combination with image analysis could also be blocked by a shielding object. Although, the camera would be able to detect a shielding object and send a signal to stop the charging if that was the case. Furthermore, the camera lens is sensitive to dirt and using a camera is the most complex and expensive method.

Ultrasonic distance sensors work by sending a directional burst of ultrasonic sound and then measuring the time until an echo returns. An advantage of using this sensor is that it can be placed horizontally. This is because the distance measurement allows the sensor to distinguish between an object inside versus and object outside the dangerous area. A downside is that the sensitivity is dependent on the surface properties of the object. They work best with hard flat surfaces. Sound absorbent surfaces like fur gives reduced range and area of detection.

Ultrasonic tripwires are pairs of ultrasonic transmitters and receivers that send pulses between them. If an object is between them, it will block and deflect the sound. The decrease in amplitude of the sound will then be detected by the receiver. Multiple receivers can listen to the same transmitter to give better coverage. However, sufficient coverage requires many sensors. A side effect of this is that the electronics needed increases with every added sensor. Another downside shared by both ultrasonic tripwires and distance sensors is that they will detect inanimate objects as well as live beings.

A decision was made to use a combination of ultrasonic distance sensors and tripwires. This do not require a position on the underside of the car, nor do they require special ground clearance, as cameras and heat sensors do. Having the sensors built-in to the car rather than in the charging stations would require more of them. This is because there will be more cars than charging stations. It would also require adding wireless communication to the system. Adding ground clearance for the sensors makes it likely that they eventually will be damaged, by for example accidentally be hit by the car when parking. The main reason to use them rather than motion detectors was that ultrasonic distance sensors enables the system to know when the live being detected has left the dangerous area. In comparison, false alarms from inanimate objects, which is possible with ultrasonic distance sensors, is a smaller issue since the detection area will be under a car. It will also be possible to detect larger conductive objects making the conductive objects detection subsystem more reliable. Another advantage of using both distance sensors and tripwires is that the ultrasonic pulse from the distance sensors can be used as the transmitter for the tripwires. A combination of these two systems will give an increased sensor coverage and making it easier to detect sound absorbing materials like fur with the same number of sensors.

3.2 Detection of Conductive Objects

For detection of conductive objects, two common techniques were considered

- Magnetometer
- Inductive sensor

Magnetometers are used to measure the direction and strength of magnetic fields. Thus, it can be used to detect metals because of the changes in the magnetic field they cause. They are mostly used in applications with static magnetic fields such as Earth's magnetic field. However, a few sensors can measure alternating fields up to a few kHz. With the charging field being approximately 90kHz this means that an external field would have to be created using much lower frequency. However, the sensors are sensitive to alternating fields other than the one it measures because it causes interference with the detection and limits its effectiveness, [7], [8].

Inductive sensors are used in many modern metal detectors, e.g. treasure hunting and traffic light systems. These systems, also known as search coil sensors or induction loop sensors consist of two coils, a transmitter and a receiver coil. The pair functions much in the same way as a transformer. An ac voltage is applied to the transmitter coil which generates an alternating magnetic field. The receiver coil then acts as an antenna and current is induced in it. Both coils are also connected to an LC circuit using the same resonance frequency. A reference point is first established with no conductive object nearby. When a conductive object is placed in close proximity it will, as previously mentioned, cause changes to the magnetic field and the inductance of the coils. The change to the magnetic field will result in a change in the induced current. Furthermore, the change in inductance means that the system no longer operates at its resonance frequency, which will decrease the induced current. The magnitude of drop will depend on the Q factor. A larger Q factor will result in a bigger voltage drop. The conductive object will also absorb some of the magnetic energy as heat, which will cause an additional drop. Finally, there will be a phase shift in the induced current. The phase shift occurs because of the phase response of the material. An inductive material which conducts electricity easily is slow to react to changes in the current compared to a resistive material which does not conduct electricity easily.

Since the detection unit will be in close proximity to the charging field, using a magnetometer becomes problematic. A search coil sensor is deemed more reliable and will be used in this project. It is not necessary to distinguish between different types of conductive materials and it will thus not be necessary to study the phase shift. Instead, the amplitude of the induced voltage will be monitored to see if it differs from the reference value.

4

Design of Sensor Array

Ultrasonic distance sensors and ultrasonic receivers was purchased as finished components. The components are described in Chapter 5, only the placement of the sensors are discussed in this chapter. The search coil sensors was designed from scratch since suitable complete search coils was not available for purchase.

4.1 Ultrasonic

In order to maximize the number of tripwires given a certain number of sensors, all transmitters will be on one side of the charging coil, and the receivers will be on the other side, as can be seen in Fig. 4.1. The prototype will use four transmitters and four receivers. This number was considered to be enough to evaluate the concept. The project has a limited budget of both time and money, which is why using more sensors than required to evaluate the concept was deemed unnecessary.

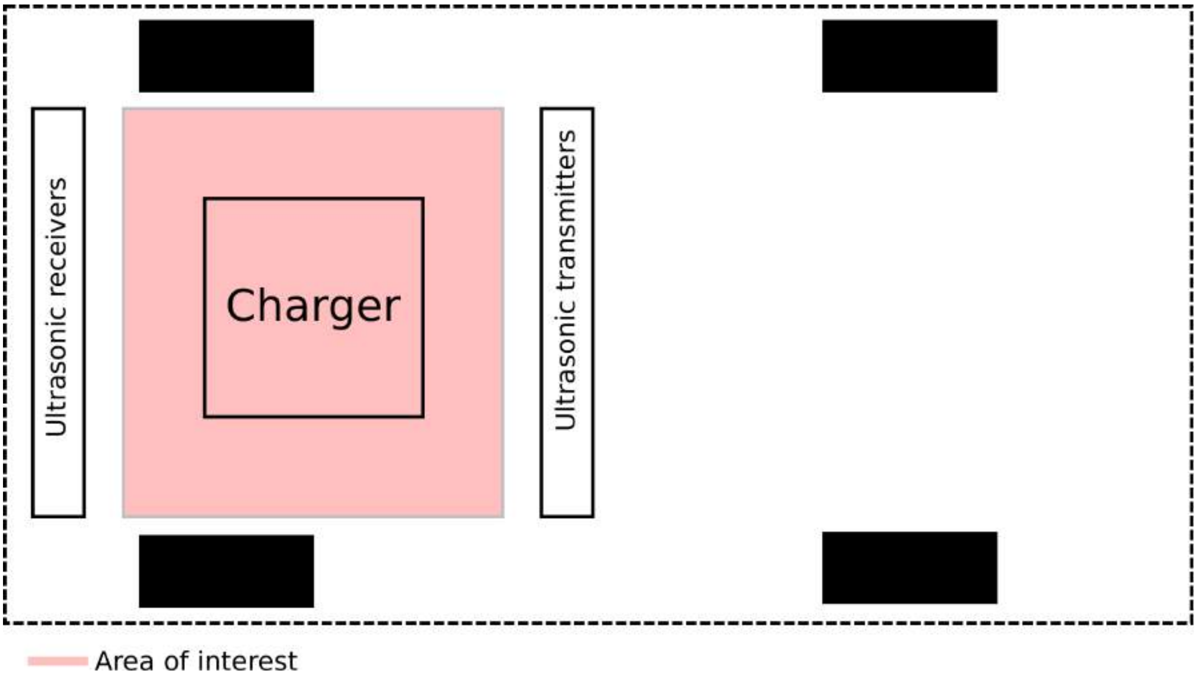

Figure 4.1: Ultrasonic sensor array

Ultrasonic tripwires can detect objects that are a short distance away from the line between the sender and receiver. This distance depends on how sensitive the measurement circuit is and how strong the base signal is. The base signal depends on several factors: strength of the transmitter, sensitivity of the receiver, distance between them, angle between them, and signal noise. The performance of ultrasonic distance sensor varies with the geometry and surface properties of the object to be detected.

These uncertainties in sensor performance make it hard to predict how many sensors will be required in order to always detect an object 10 cm in diameter. In Fig. 4.2 shows the worst-case scenario: that tripwires have no width, and the distance sensors are unable to detect objects. A 0.6 m by 1.3 m can be covered by four transmitters and four receivers. The distance sensors will be aimed at the areas with points furthest from a tripwire.

The prototype will be designed so that both the transmitters and receivers can be moved relative to each other. This in order for it to be possible to determine how large an area can be covered with four sensor-pairs.

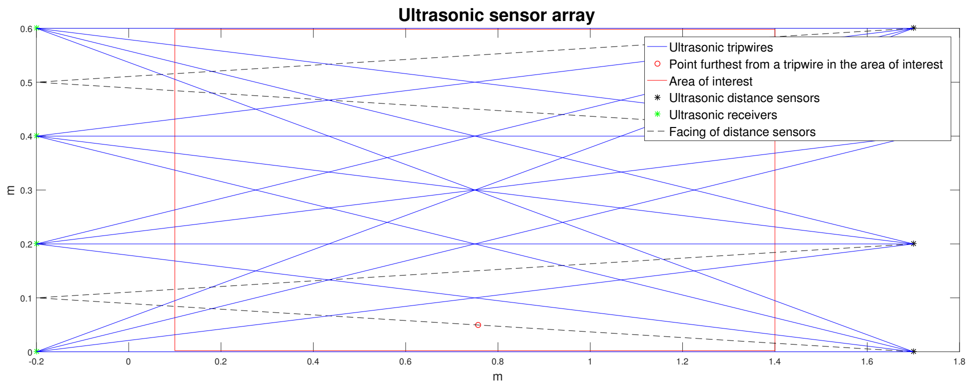

Figure 4.2: Ultrasonic sensor array

4.1.1 Environment Protection in Final Production Version

Although the prototype is not required to be able to withstand being run over by a car or enduring harsh weather, the concept should still be able to be modified for such use. In Fig. 4.3, a basic sketch-up of how the sensors could be protected is shown. The housing material could, for example, be concrete, which should be able to withstand being run over by a car. Waterproof ultrasonic distance sensors are commercially available.

Figure 4.3: Physical placement mock-up

4.2 Search Coil Sensor

The details of the search coil sensor design and placement are discussed here.

4.2.1 Basics

Sensitivity and detection depth of a search coil sensor depend on the dimensions of the transmitter and the receiver coils. For an object the size of a coin, the detection depth is approximately equal to the diameter of a circular coil, or the shortest side of a rectangular coil. However, if the detection depth is increased, the sensitivity is decreased too. This is because the magnetic field becomes less concentrated, meaning less induced current and a smaller magnetic field from the object. The ability to detect a coin-sized object is lost at a diameter approximately between $30 - 40$ cm. Since the desired detection area is larger than this, it will be necessary to use multiple smaller sensors in order to detect objects small enough. With this in mind, a rectangular shape will then be able to cover the desired area more effective than a circular one.

The receiver coil should be less than or equal in size to the transmitter coil, and placed within it. The area in which the sensor can detect conductive objects equals the area of the receiver coil. However, a larger area will enable the coil to pick up more noise, which decreases sensitivity. As multiple sensors will be used, a problem concerning blind zones occurs which is visualized in Fig. 4.4.

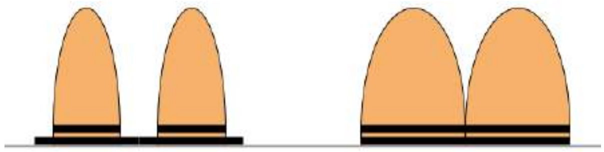

Figure 4.4: Different receiver coil sizes and their detection zones

When the receiver coil is smaller than the transmitter coil, there will be a blind zone between two sensors where neither can detect an object. This can be dangerous as large objects could potentially be missed. Because of this they will be made of equal size as shown in the design to the right in Fig. 4.4

4.2.2 Induction Balance

The effect on the magnetic field generated by the transmitter by a conductive object will be small. In order to measure this effect, the signal induced in the receiver coil will have to be amplified. However, with the transmitter inducing a base level voltage, this signal can not be amplified much before reaching the limit imposed by the supply voltage. To counter this a technique known as induction balance will be used, [10]. The goal of the induction balance is to make the coupling between the transmitter and receiver coil zero, while keeping the coupling to conductive objects in the vicinity non-zero. Meaning no current will be induced in the receiver by the transmitter field. But current will still be induced by conductive objects. To achieve induction balance, a 'Figure-8' coil will be used, as seen in Fig. 4.5.

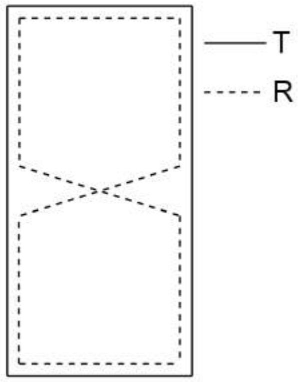

Figure 4.5: 'Figure-8' coil

The receiver coil is twisted to form a 'Figure 8'. The transmitter field will then induce a positive current in one half of the receiver and a negative in the other. These two will cancel each other out and give a net current of 0. The disadvantage with this configuration is that there will be a small blind spot in the center where the two halves meet, where the metal induced field affect both halves equally.

4.2.3 Design Parameters

The coils will be drawn on a Printed Circuit Board (PCB) in a spiral pattern. This will make the induction balance more accurate, compared to winding the coils by hand. The width of the transmitter is set to $15cm$. The receiver coil will consist of two squares with length equal to the width of the transmitter, $15cm$. This makes the length of the transmitter coil as $2 \cdot 15 = 30cm$. When determining the number of turns there are two things to consider: inductance vs resistance. Increasing the number of turns will increase the inductance, which will make the magnetic field stronger for a constant current. However, more turns also means more resistance in the coil, which decreases the Q factor as shown in Eq. 2.11, lowering the current through the coil. General guidelines when building a search coil often state that $10 - 20$ turns will give good performance, [11]. These guidelines were used as basis for the decision and 15 turns were chosen.

The prototype will use a total of three search coil sensors. The transmitter coils will all be connected to the same source. This simplifies the circuit and uses fewer components. The coils can be connected in either series or parallel. Each transmitter coil will be connected in series with a capacitor to form a resonance circuit. When connected in this manner, the complex impedance for the coils and the capacitors will cancel each other out leaving only the resistance in the circuit. This gives the equivalent resistance as

$$R_{eq,s} = R_1 + R_2 + R_3 \tag{4.1}$$

for a series configuration and

$$\frac{1}{R_{eq,p}} = \frac{1}{R_1} + \frac{1}{R_1} + \frac{1}{R_1} \rightarrow R_{eq,p} = \frac{R_1 R_2 R_3}{R_1 R_2 + R_1 R_3 + R_2 R_3} \tag{4.2}$$

for a parallel configuration, with index 1, 2, and 3 corresponding to coil 1, 2, and 3. The coils will be identical in size and shape and thus $R_1 = R_2 = R_3 = R$, and Eq. 4.1, and 4.2 simplifies to

$$R_{eq,s} = 3R \tag{4.3}$$

and

$$R_{eq,p} = \frac{R}{3} \tag{4.4}$$

As can be seen in Eq. 4.3 and 4.4, a parallel configuration gives much lower equivalent resistance and will result in a higher current. The design can be seen in Fig. 4.6

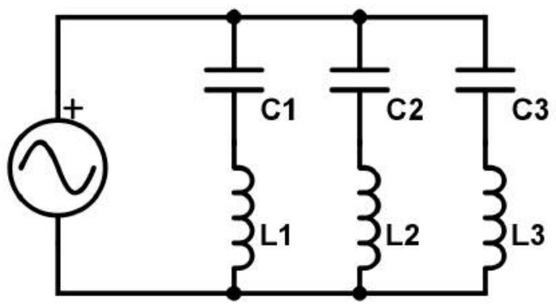

Figure 4.6: Transmitter coils

The receiver coils will also be connected to one circuit used for detection. As is the case for the transmitter this simplifies the circuit. Furthermore, it means that only one signal needs to be monitored, compared to the ultrasonic subsystem using many sensors, needing individually monitoring. The receiver coils will be connected in series. Whether this will influence the sensitivity will be studied. To enable this it will be possible to disconnect one or more coils. The design can be seen in Fig. 4.7

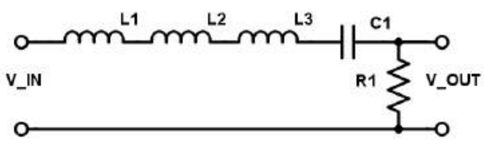

Figure 4.7: Receiver coils

As for the transmitter coil, a resonance circuit is formed by connecting the coils in series with a capacitor. The receiver side also has a resistor in series. The voltage across this resistor will be the output that will be measured.

4.2.4 Operating Frequency

For the choice of operating frequency a few constraints can be formulated. Metal detectors usually operate in the frequency range $10 - 200kHz$, [13]. This sets the first constraint. Standards concerning electromagnetic emissions, compatibility and interference becomes more severe at $150kHz$ where these aspects may be needed to take into considerations when designing the electronics, []. To avoid this the operating frequency will be below $150kHz$. Next the charging station will operate at approximately $90kHz$. To minimize interference between the two systems the two operating frequencies should be kept at some distance from each other.

The search coil design will be fixed. This means that the inductance, L, and the series resistance, R, of the coils is fixed leaving only the capacitance, C as variable. Recall equation 2.11 for the Q factor and equation 2.8 for the resonance frequency. Decreasing the value of C means a larger Q factor and a higher frequency. A large Q factor is desirable for maximizing the current through the coils. The operating frequency is therefore chosen to be above $90kHz$. The operating frequency is then chosen to be between $130 - 140kHz$ leaving some margin up to $150kHz$ because of non-ideal components.

4.2.5 Placement

The placement of the search coil sensors will be done as shown in Fig. 4.8.

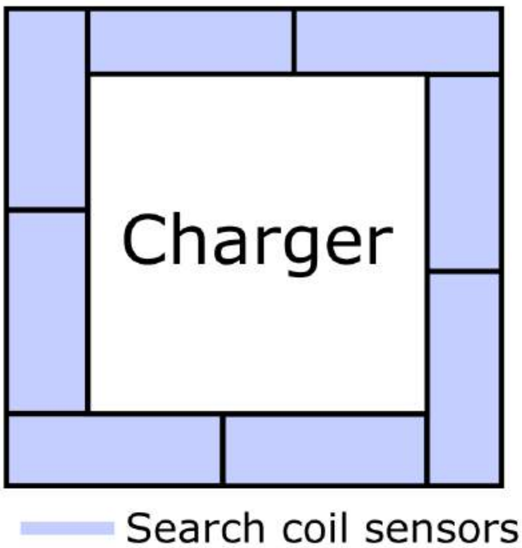

Figure 4.8: Placement of search coil sensors

The sensors will be placed next to each other in such a way that their are no gaps between two sensors. They will then monitor if a conductive object is about to enter the charging area.

4.2.6 Input and Output

Both the input and the output to the search coil sensor will be an ac voltage. The input is applied to the transmitter coil and the output is obtained at the receiver coil.

5
Electronics Design

This chapter will list the electronics that were needed for the detection unit, which components they use and their values. Fig. 5.1 shows a flowchart of the functionality of the detection unit.

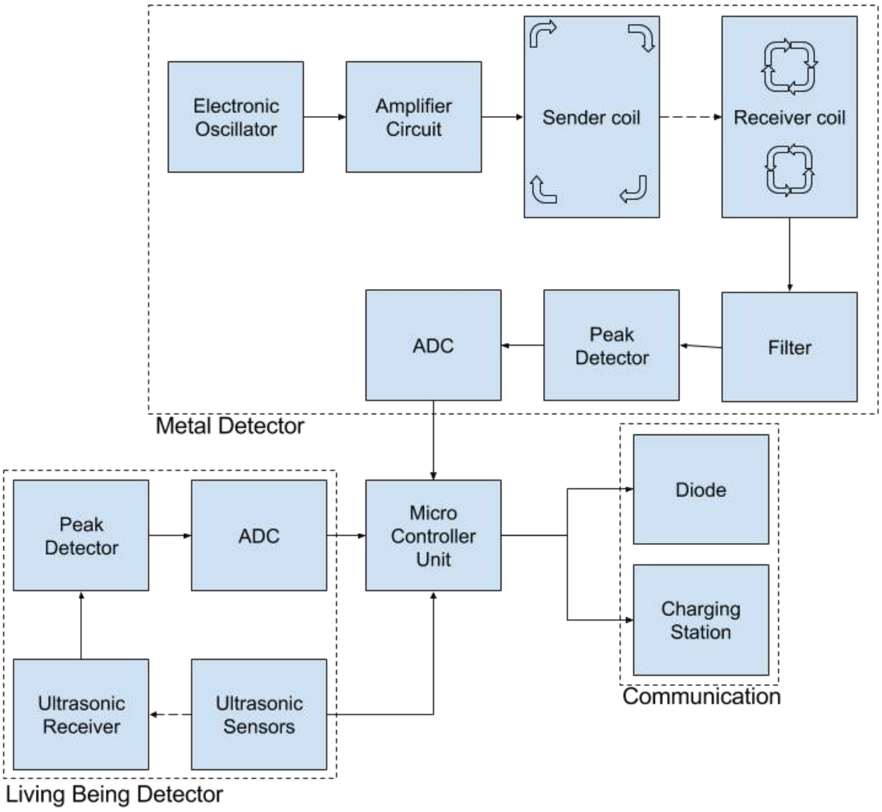

Figure 5.1: Flowchart of detection unit

It can be regarded as three separate parts, detection of conductive objects, detection of live beings, and communication. All of these parts are processed by a microcontroller unit (MCU). The MCU monitor the two detection systems separately, and if either reports a detection, communicate this to the charging station and user. The design layout of the detection unit can be described roughly using Fig. 5.2.

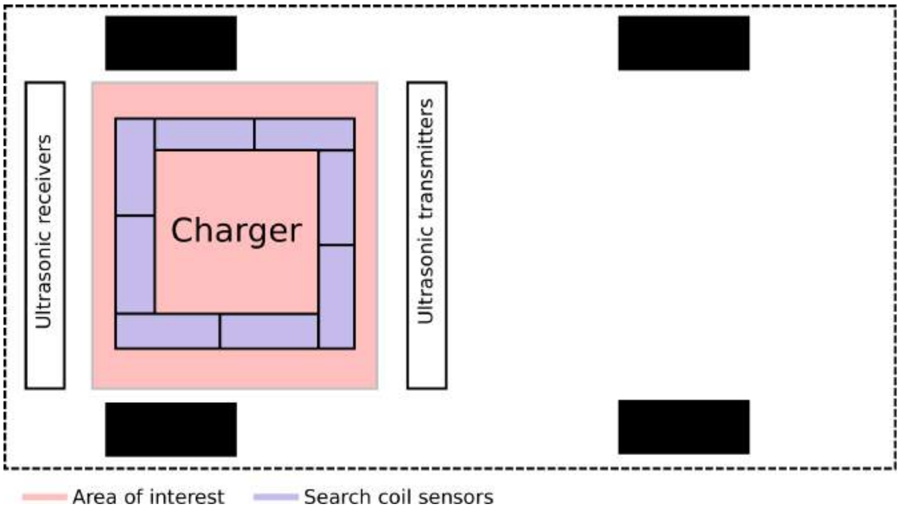

Figure 5.2: Detection unit layout

The search coil sensors are placed around the charging unit. They are connected to a printed circuit board (PCB) containing all subparts for the conductive object detection, as well as the MCU. The ultrasonic sensors are connected directly to the MCU using one of its digital pins each. They are also disconnected from the rest of the electronics, to allowing change of positions. Each ultrasonic receiver is placed on a PCB of their own. Each PCB contains their own separate set of the subblock Peak Detector. The receivers are placed close to an external Analog-to-Digital Converter (ADC) in order to minimize the length of the analog signal lines. Finally, the ADC is connected to the MCU using digital pins.

5.1 Power Supply

Input to the PCB will be a 12V dc voltage supplied from an external power supply. Some components, like the MCU, require 5V. Thus a voltage regulator was needed. For this, an LM7805 linear voltage regulator from Fairchild was chosen. It uses three pins, input voltage, ground, and output voltage. The input voltage has a maximum limit of 35V. The output voltage is fixed at 5V, and can deliver up to 1A of continuous output current.

5.2 Detection of Live Beings

This section lists the electronics that was used for the live being detection system.

5.2.1 Ultrasonic Sensors

For the ultrasonic sensors, the PING))) Ultrasonic Distance Sensor from PARALLAX was chosen. Equipped with both a transmitter and a receiver, it has a detection range of 2cm to 3m. This sensor was chosen for its simple design using only three pins. Two pins are for 5V and ground, while the last one is the signal pin. The signal pin can be connected directly to an MCU using one digital pin. To start a measurement, a trigger pulse of 5μs is sent to the sensor. The sensor then transmits a 40kHz ultrasonic burst, and listen for the echo. A return pulse, (an echo of the transmitted ultrasonic burst), is then sent back on the signal pin. The length of the pulse ranges between 115μs and 18.5ms, and is the time it takes for the echo to return. Since the echo has travelled to the object and back, the time it takes to reach the object will be half of the pulse length. This time can be transformed into a distance with Equation 5.1

$$d = v \cdot \frac{t}{2} \tag{5.1}$$

where v is the speed of sound, approximately 340m/s.

5.2.2 Ultrasonic Receivers

The separate ultrasonic receiver chosen was the MA40S4R from Murata Electronics. It operates on the same frequency as the ultrasonic sensor - 40kHz. When the receiver picks up an ultrasonic pulse it starts to oscillate. The amplitude of these oscillations depend on how much signal it picks up from the sensor. Fig. 5.3 and 5.4 shows the pulse at two distances.

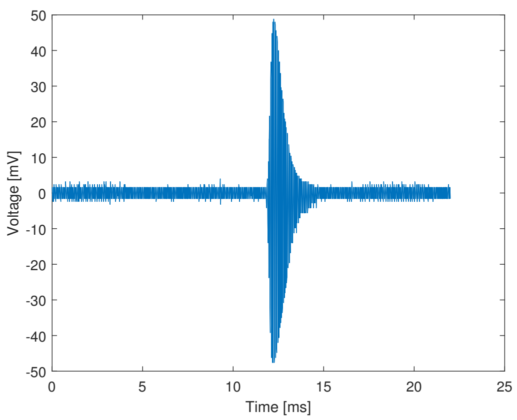

Figure 5.3: Receiver signal at 1m

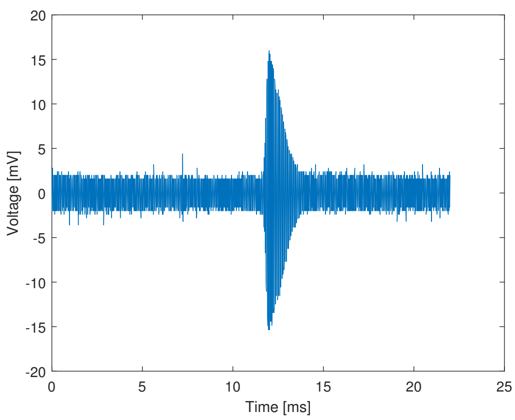

Figure 5.4: Receiver signal at 2m

5.2.3 Peak Detectors

The output from the ultrasonic receivers is connected to a peak detector circuit shown in Fig. 5.5.

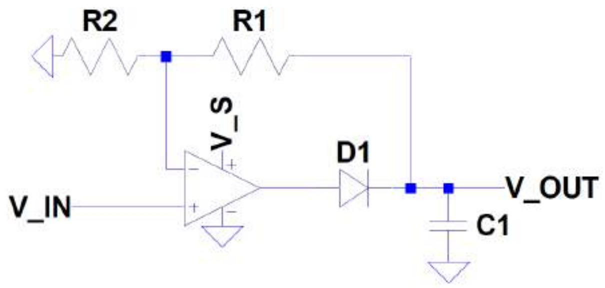

Figure 5.5: Peak detector circuit

A peak detector is used to convert an ac voltage into a dc voltage equal to the maximum value of the ac voltage. The capacitor C_1 is charged up to the peak value of the ac voltage. When the capacitor is charged so that its voltage is larger than the voltage source, the diode D_1 prevents current from flowing back toward the voltage source. Thus, the voltage level can be sustained. However, since the capacitor slowly discharges, the voltage level cannot be sustained indefinitely. In a real application, the diode will be non-ideal resulting in a voltage drop across it. This drop causes the dc level to be below the peak value of the ac voltage.

This circuit acts as an amplifier as well. The operational amplifier is used in a non-inverting configuration, [12]. Using Kirchhoff's current law, the amplification of the operational amplifier is calculated using Equation 5.2

$$V_{out} = \left(1 + \frac{R_1}{R_2}\right) V_{in} \tag{5.2}$$

The LTC6240 from Linear Technology was chosen as the operational amplifier. It can be powered from a single supply of 5V. It has both Rail-to-Rail input and output, meaning both input and output voltages can range between the supply rails. The gain bandwidth product (GBP) of the amplifier is 18MHz and the operating frequency of the receivers is as mentioned 40kHz. This relationship sets the potential maximum allowed amplification as

$$A_{max} = \frac{GBP}{f} = \frac{18M}{40k} = 450 \tag{5.3}$$

The operating range is approximately 2 meters. As seen in Fig. 5.3 the voltage at that distance is approximately 15mV. To have some margin if the distance would be decreased, an amplification of 100 was chosen. This give an expected output signal of 1.5V which is below the maximum allowed voltage of 5V. Resistor values are then chosen as $R_1 = 100\text{k}\Omega$ and $R_2 = 1\text{k}\Omega$, resulting in an amplification of 101. The larger the value of C_1, the longer it will take for the capacitor to charge and discharge. Through testing it was chosen as 1μF. Diode D_1 was chosen as an N5817 Shottky diode because it has a low forward voltage drop.

The input signal is also centered around 0V. The datasheet of the operational amplifier specifies input voltage tolerances. The minimum allowed voltage is -0.3V, and the maximum allowed voltage is 0.3V above the supply voltage. If the receiver is close enough to the sensor, this will be surpassed. As a safety measure a diode was added as a reverse current protection as shown in Fig. 5.6.

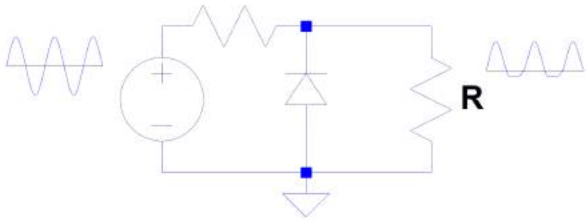

Figure 5.6: Reverse Current Protection

When the voltage is positive the diode blocks, as the current can not flow in that direction. When the voltage is negative, the circuit gets shorted and oppose the negative voltage. For an ideal diode, the voltage across the load will be zero. However, this will not be the case in a real system. All diodes have a forward voltage drop, i.e. the voltage drop across the diode. This voltage drop is equal to the lower output voltage limit, as shown in Fig. 5.6. An N5817 Shottky diode was chosen here as well. According to the datasheet, its voltage drop at 100mA is below 0.25V. Since the receiver has a high output impedance, it will give a low current, and the voltage drop will be sufficiently small to not surpass the -0.3V minimum rating of the operational amplifier.

5.2.4 External ADC

The output from the peak detectors is connected to an external ADC. It converts the analog output from the peak detectors to a digital one that the MCU can read. The chosen ADC is an MCP3204 from Microship Technology. It has four channels, one for each receiver, and a 12-bit resolution. The input must be positive, and below the reference voltage of the ADC. The maximum value that can be obtained from the peak detectors is 5V since this is the supply voltage for the operational amplifier. Therefore, the reference voltage is set to 5V as well. Therefore the resolution is $\frac{5}{4096} = 1.2$mV. When an object is placed between the sensor and the receiver, it blocks most of the signal. The resolution should therefore be sufficient to determine that a detection has been made.

The communication with the MCU is done using Serial Peripheral Interface, SPI, which is an interface bus used for communication between devices. It uses four signals, CLK, CS, MOSI, and MISO. CLK is the serial clock and is used to synchronize the ADC and the MCU, and when they should sample data. CS is the chip selector and is used when communicating with multiple devices. Each device has its own chip select signal. When held high, that device is disconnected from the bus, and when held low it gets connected to the bus and can transmit data. MOSI and MISO forms the SPI bus. MOSI stands for Master Output Slave Input and is used to send information from the master (MCU) to the slave (ADC). MISO stands for Master Input Slave Output and is the opposite of MOSI and used to send information from the slave to the master.

5.3 Detection of Conductive Objects

The conductive objects detection system consists of two subsystems, sender and receiver.

5.3.1 Electronic Oscillator

The input to the system is a dc voltage, which needs to be converted into an ac voltage. To accomplish this an electronic oscillator was chosen. It is a type of circuit capable of transforming dc to ac, with a desired frequency and wave shape. For a sinusoidal output in the radio frequency (3 kHz - 300 GHz) domain, the most used oscillator circuit is the LC oscillator [17]. In an LC oscillator, the oscillating part is an LC resonance circuit with an inductor and a capacitor. The design of LC oscillators varies but the two most commonly used ones are the Hartley and Colpitts oscillators shown in Fig. 5.7 and 5.8.

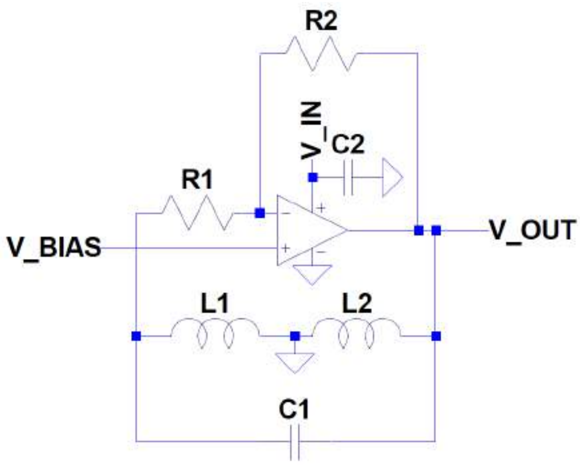

Figure 5.7: Hartley Oscillator

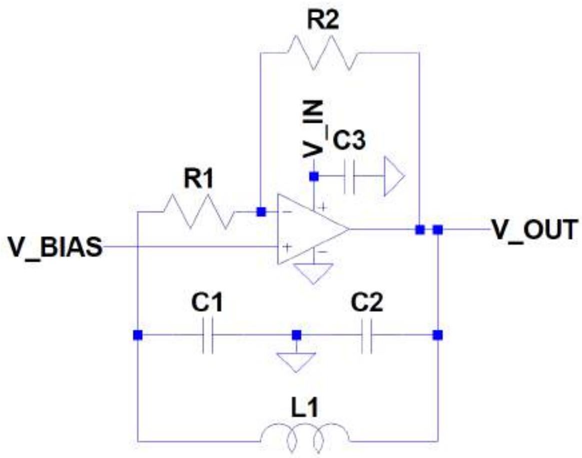

Figure 5.8: Colpitts Oscillator

They are similar in both functionality and appearance. The difference is the LC circuit consisting of one inductor and two capacitors for the Colpitts and the opposite for the Hartley oscillator. Changing the frequency is a matter of changing value of the inductance, the capacitance, or both, and requires no software. Because the Colpitts oscillator only have one inductor, the circuit has less self inductance, and less mutual inductance, which gives greater frequency stability. Therefore, the Colpitts oscillator was chosen for this application.

The frequency of the oscillations is decided by the LC circuit through

$$f = \frac{1}{2\pi\sqrt{L_1 C_{tot}}} \tag{5.4}$$

where C_{tot} is C_1 and C_2 in series and equals

$$C_{tot} = \frac{C_1 C_2}{C_1 + C_2} \tag{5.5}$$

Because of resistive losses in the system, an amplifier component is needed to maintain the oscillations. The Linear Technology LT1632 operational amplifier was chosen for this purpose. It can be powered from a single supply and has both Rail-to-Rail input and output. The negative supply rail is grounded. Therefore, a voltage bias is required for the oscillation. If no bias is present, the output only have a negligible range (down to ground) during the negative phase of the oscillations. A voltage bias can be implemented by using a voltage divider as shown in Fig. 5.9.

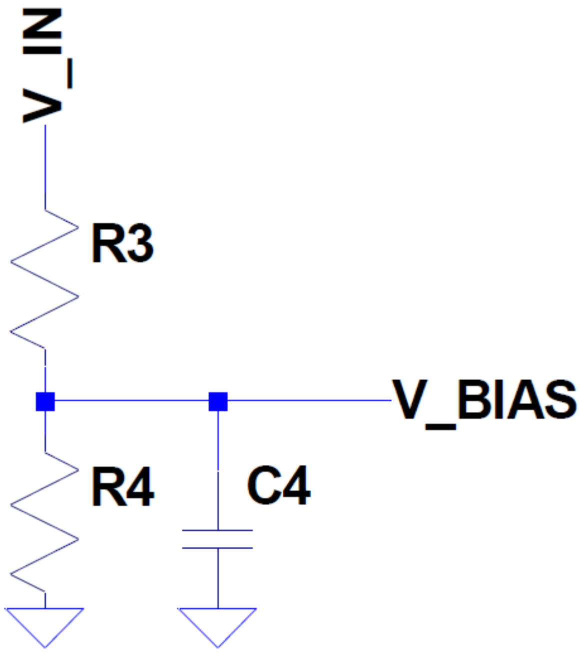

Figure 5.9: Bias for the Colpitts oscillator

The voltage bias is calculated as

$$V_{bias} = \frac{R_4}{R_3 + R_4} V_{in} \tag{5.6}$$

Choosing $R_3 = R_4$ gives $V_{bias} = \frac{V_{in}}{2}$. The actual value of the resistors are of less importance, only that they have the same value. 10kΩ was thus chosen. The capacitors C_3 and C_4 are called decoupling capacitors. Their purpose is to filter out noise caused by the other circuits and make the voltage smoother. A typical value of a decoupling capacitor is 100nF-0.1μF, [16]. 100nF was thus chosen for both C_3 and C_4. Through testing R_1 is set as 10kΩ and R_2 as 100kΩ.

5.3.1.1 Choice of Frequency

The desired operating frequency was determined in section 4.2.4 to lie between 130 − 140kHz. Furthermore an inductor of 150μH, having a series resistance of approximately

10Ω, was chosen for the LC-circuit. The necessary capacitance, for a frequency of 135kHz, can then be calculated as

$$C_{tot} = \frac{1}{4\pi^2 f^2 L} = \frac{1}{4\pi^2 135000^2 150\mu} = 9.27\text{nF}$$

Then if choosing C_2 as 100nF the value of C_1 can be calculated as

$$C_1 = \frac{C_{tot} C_2}{C_{tot} - C_2} = \frac{9.27\text{n}100\text{n}}{9.27\text{n} - 100\text{n}} = 10.2\text{nF}$$

Closest value is then 10nF.

5.3.1.2 Simulation

The simulations in this section was performed using LTspice.

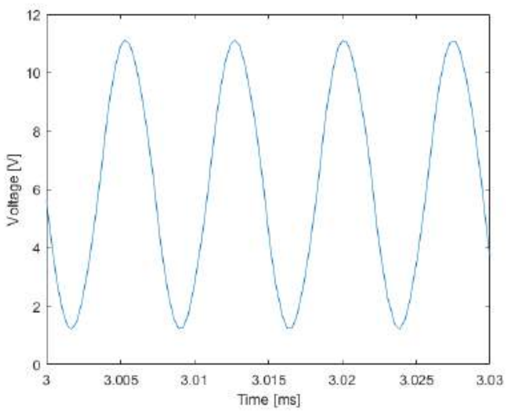

Figure 5.10: Simulation of output from Colpitts oscillator with an ideal inductance

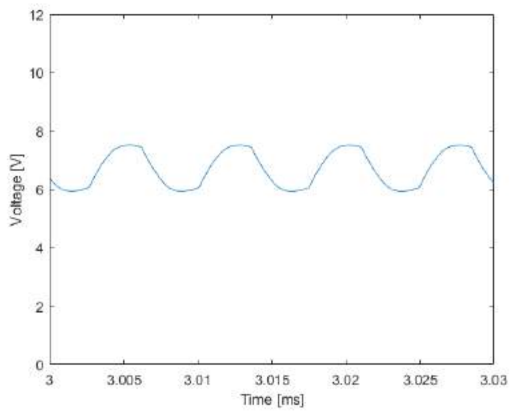

Figure 5.11: Simulation of output from Colpitts oscillator with an non-ideal inductance(10Ω series resistance).

Simulation of the oscillator yields the graphs above. Fig. 5.10 shows the output from the oscillator without series resistance in the inductor, and Fig. 5.11 shows the output from the oscillator with series resistance in the inductor. As can be seen the series resistance cause a decrease in amplitude from 10V peak-to-peak, with a max value of 11V, to 1.5V peak-to-peak with a max value of 7.5V. There are also some distortions to the voltage. The distortions will be ignored because they are relatively small. The amplitude of the oscillator will be increased by the use of an amplifier circuit as seen in Fig. 5.12.

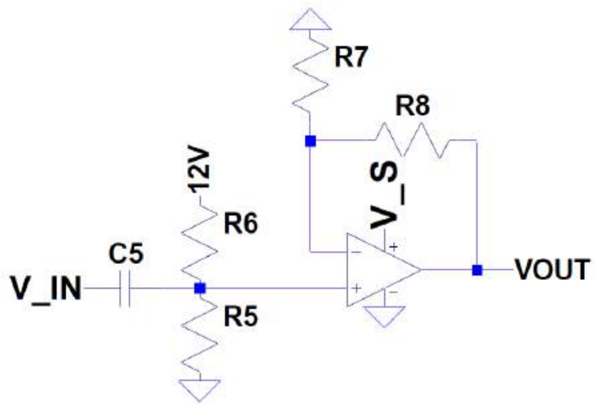

Figure 5.12: Amplifier for the Colpitts oscillator

Firstly, the bias of the signal from the Colpitts-oscillator is removed in order to allow a larger amplification. This is achieved by placing the capacitor C_5 in series with the input, since a capacitor acts as a open circuit for dc voltages. C_5 was chosen as 1nF. Secondly, a new, much smaller, bias is added to avoid negative voltage on the input to the op amp, as shown in Fig. 5.12. This is accomplished through a voltage divider with $R_5 = 10k\Omega$, $R_6 = 110\text{k}\Omega$, and $V_s = 12\text{V}$ which will give a bias of

$$V_{bias} = \frac{R_5}{R_5 + R_6} V_s = \frac{10\text{k}}{10\text{k} + 110\text{k}} \cdot 12 = 1\text{V}$$

The LT1632 operational amplifier is a dual amplifier. This means that one package contains two amplifiers. Since the Colpitts Oscillator only uses one, the second one will be used for the voltage amplifier in Fig. 5.12. The amplification is set using $R_7 = 1\text{k}\Omega$ and $R_8 = 5100\Omega$. According to Kirchhoff's current law, this will result in an amplification of

$$\frac{V_{out}}{V_{in}} = 1 + \frac{R_8}{R_7} = 1 + \frac{5100}{1k} = 6.1$$

This results in an input signal of $1 \pm 0.75\text{V}$, and an output signal of $6.1 \pm 4.6\text{V}$, being within the supply range of 12V of the operational amplifier. With the addition of the amplifier, a new simulation is performed yielding the following result.

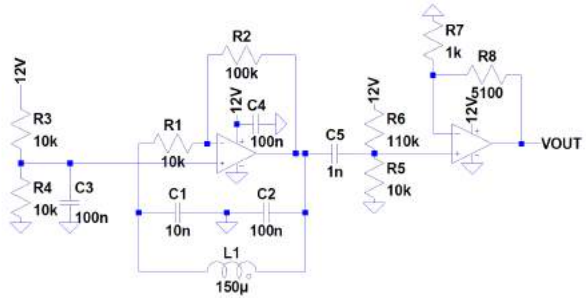

Figure 5.13: Colpitts Oscillator with amplifier

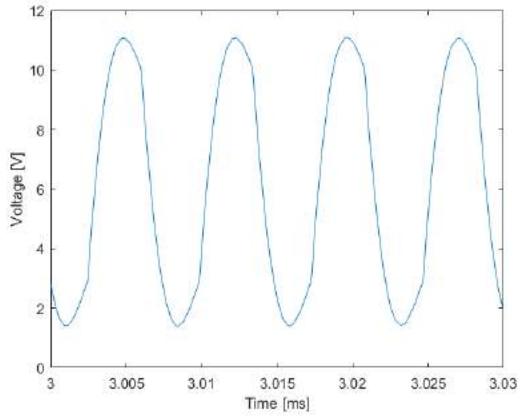

Figure 5.14: Output voltage

As shown in Fig. 5.14, the voltage is amplified and ranges from approximately 1.5 V to 11 V, which is close to the expected.

5.3.2 Transmitter Amplifier

When adding a 100Ω load at the output of the oscillator the following behaviour can be observed.

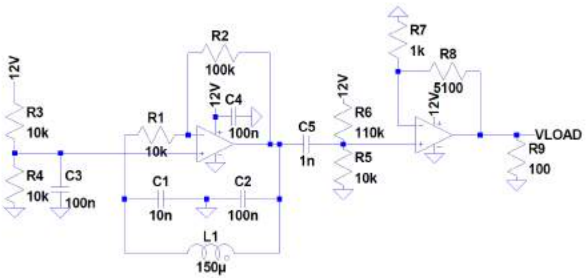

Figure 5.15: Colpitts Oscillator with load

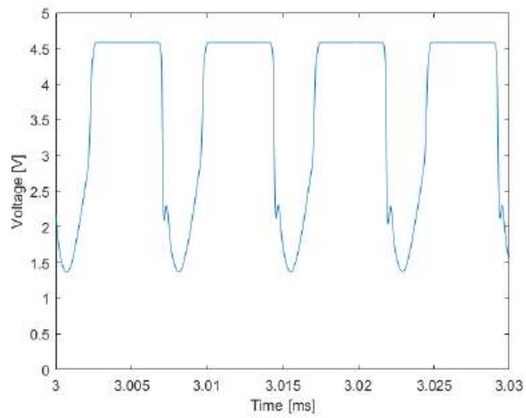

Figure 5.16: Output voltage

The output voltage gets limited to 4.5V. This is because the LT1632 can only give a 45mA output current. Therefore, the output voltage reduced, as Ohm's law states that

$$V = RI \tag{5.7}$$

The magnetic field generated by the transmitter coil is proportional to the current running through it. In addition, a stronger magnetic field makes it possible to detect smaller objects. Thus, a second amplification stage will be needed in order to provide the necessary current. With proper component choice a transistor-based amplifier can give an output current of several amperes. Therefore it is preferred to use a transistor-based amplifier rather than an operational amplifier which can rarely accomplish this. For the application, a Push-Pull amplifier as shown in Fig. 5.17 was chosen.

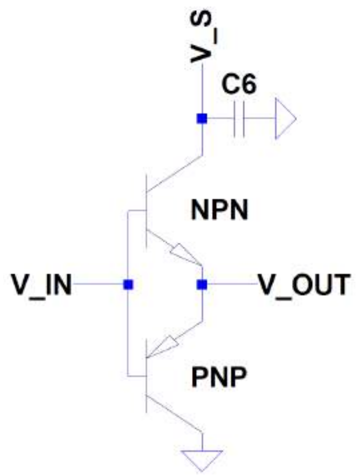

Figure 5.17: Push-Pull amplifier

The amplification is achieved using two complimentary transistors - one being an NPN type and the other a PNP type. When the emitter voltage, V_{out}, is greater than the base voltage, V_{in}, the NPN transistor is on while the PNP is off. This will then source current from the supply to the load. When V_{out} is less than V_{in} the NPN transistor will be off while the PNP is on. The amplifier will then instead sink current through the load. One disadvantage with this is that small distortions in the voltage can occur at the switching points of the transistors. Since the current is drawn directly from the power supply V_s, (12V), rather than the oscillator, a much larger current can be obtained. For the NPN transistor KSD526 from Fairchild is chosen and for the PNP transistor KSB596, also from Fairchild, is chosen. They can give an output current up to 4A. Capacitor C_6 is the decoupling capacitor, and its value is chosen as 10μF. The Push-Pull amplifier is added to the circuitry and the result can be seen in Fig. 5.18.

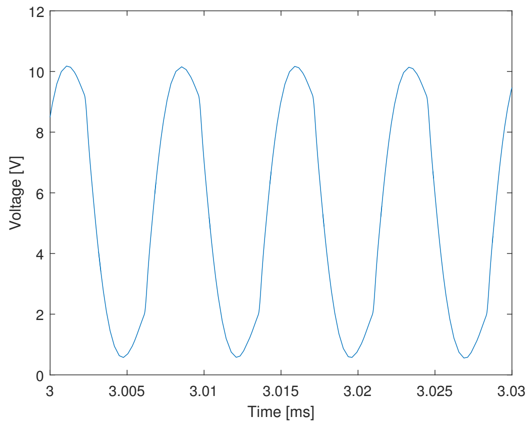

Figure 5.18: Push-Pull output with load

With the added circuitry, the voltage can be sustained at the desired voltage level, and the subsequent current is higher.

5.3.3 Transmitter Coils

Fig. 5.19 shows an illustration of one out of the three transmitter coils.

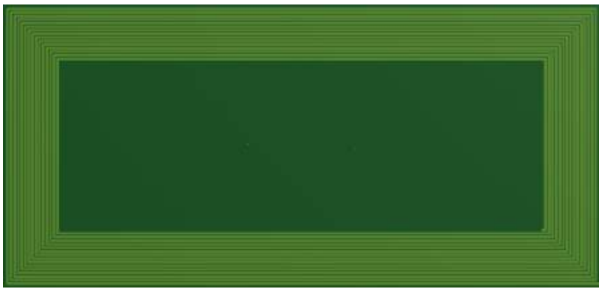

Figure 5.19: Transmitter coil

As mentioned in section 4.2, these are connected in parallel, and each of the coils is also connected in series with a capacitor. These should be matched to resonate at the same frequency as the Colpitts Oscillator, which in the real system was 146kHz rather than 136kHz (see chapter 6). To obtain the inductance of the coil, a frequency sweep, measuring the inductance of the coils, was done as shown in Fig. 5.20

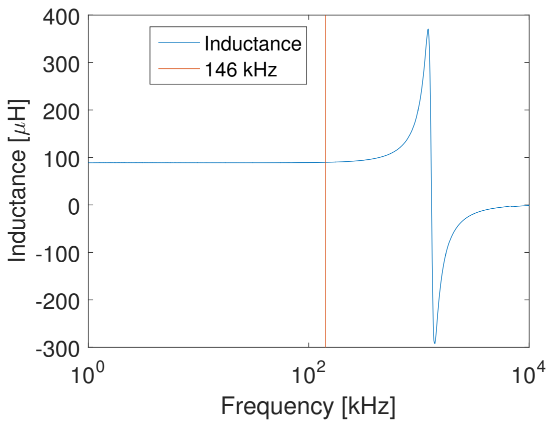

Figure 5.20: Inductance of transmitter coil at different frequencies

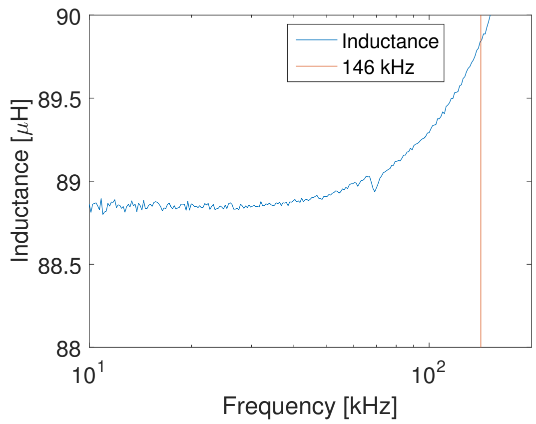

Figure 5.21: Inductance of transmitter coil at different frequencies (zoomed in)

The inductance at 146kHz is approximately 89.8μH. The necessary capacitance was calculated as

$$C = \frac{1}{4\pi^2 f^2 L} = \frac{1}{4\pi^2 \cdot (146000)^2 \cdot 89.8\mu} = 13.23\text{nF}$$

In order to get close to this value, several capacitors was needed. These are connected according to Fig. 5.22

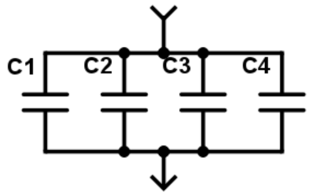

Figure 5.22: Transmitter side capacitance

with values $C_1 = 6.8$nF,$C_2 = 4.7$nF, and $C_3 = C_4 = 1$nF. Thus the equivalent capacitance can be calculated as

$$C_{eq} = C_1 + C_2 + C_3 + C_4 = 13.5\text{nF} \tag{5.8}$$

which is close to the desired value. Since the coils are connected in parallel, the same capacitor configuration can be used for all three coils. The coil and its capacitance is added as load and simulated yielding Fig. 5.23

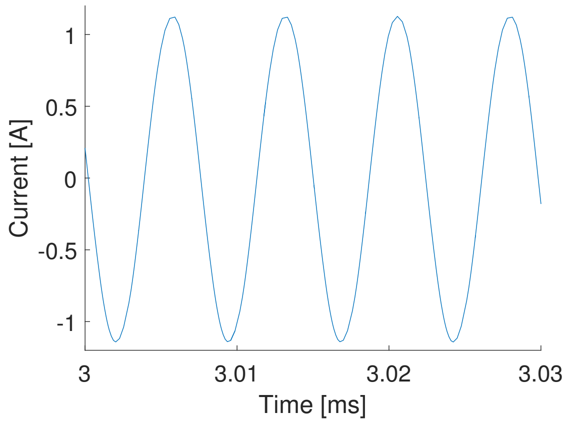

Figure 5.23: Simulation of current through one coil

It shows that approximately 2.2A peak-to-peak should flow through the coil.

5.3.4 Receiver Coils

Fig. 5.24 shows an illustration of one out of the three receiver coils which are located on the opposite side of the transmitter coil.

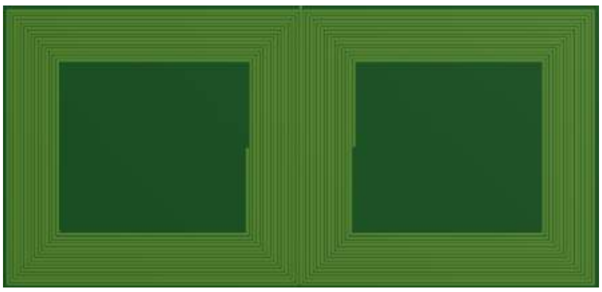

Figure 5.24: Receiver coil

As for the transmitter coil, a frequency sweep to measure the self inductance, was performed for the receiver coil as well which is shown in Fig. 5.25

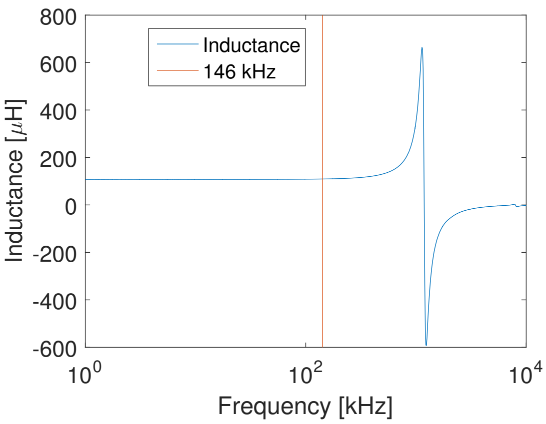

Figure 5.25: Inductance of receiver coil at different frequencies

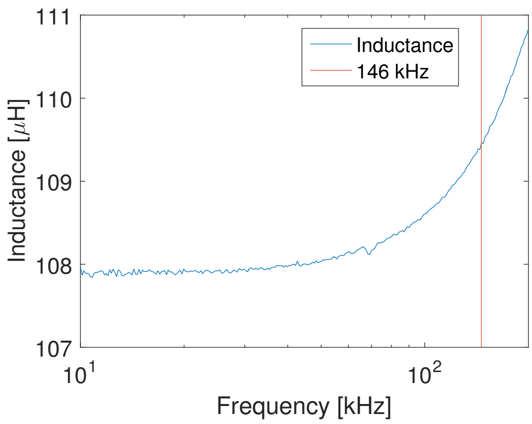

Figure 5.26: Inductance of receiver coil at different frequencies (zoomed in)

The inductance at 146kHz is 109.5μH. The receiver coils are connected in series. This means that the necessary capacitance to form resonance depends on the number of coils connected. Therefore the total inductance equals

$$L = n \cdot 109.5\mu\text{H}$$

where n is the number of coils connected. The required capacitance can then be calculated as

$$C_{1c} = \frac{1}{4\pi^2 f^2 L} = \frac{1}{4\pi^2 \cdot (146000)^2 \cdot 1 \cdot 109.5\mu} = 10.85\text{nF}$$
$$C_{2c} = \frac{1}{4\pi^2 f^2 L} = \frac{1}{4\pi^2 \cdot (146000)^2 \cdot 2 \cdot 109.5\mu} = 5.43\text{nF}$$
$$C_{3c} = \frac{1}{4\pi^2 f^2 L} = \frac{1}{4\pi^2 \cdot (146000)^2 \cdot 3 \cdot 109.5\mu} = 3.62\text{nF}$$

for one, two and three connected coils. Capacitors are then connected as shown in Fig. 5.27-5.29

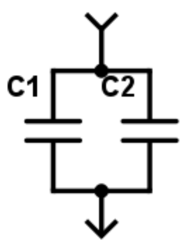

Figure 5.27: Capacitors for one coil

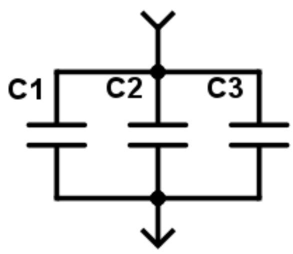

Figure 5.28: Capacitors for two coils

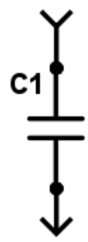

Figure 5.29: Capacitor for three coils

with $C_1 = 10\text{nF}$, and $C_2 = 1\text{nF}$ for one coil, $C_1 = 3.3\text{nF}$, $C_2 = C_3 = 1\text{nF}$ for two coils and $C_1 = 3.3\text{nF}$ for three coils.

The resistor the voltage will be measured across was chosen as 1Ω to give small effect on the Q factor.

5.3.5 Filter

The purpose of the search coil system is to operate in close proximity to the charging station. Therefore, the magnetic field from the charger can interfere with the detection, and create distortions in the signal. A band-stop filter centered around the frequency of the charging station can filter out this interference while the search coil operating frequency remains unaffected. The frequency of the search coil system, 146kHz, is still fairly close to the frequency of the charging station - 90kHz. Therefore, a filter with a high Q factor is needed in order to attenuate the 90kHz signal enough while leaving the 146kHz signal intact. These types of filters are called notch filters, and in Fig. 5.30 one possible implementation is shown.

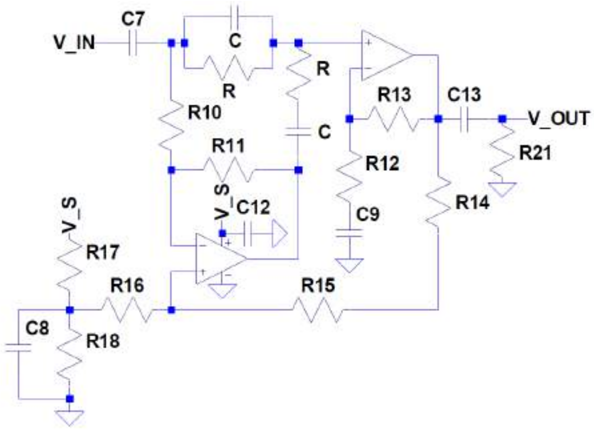

Figure 5.30: Notch Filter Schematic

The circuit is a tunable notch filter and presented in the datasheet of the Linear Technology LT1632 operational amplifier as a typical application. The component values were taken from the proposed circuit in the datasheet with the exception of R and R_{15}. Also C_{12} were added as a decoupling capacitor and C_{13} and R_{21} for bias removal. Component values from the datasheet were

Table 5.1: Notch filter component values

C	C_7	C_8	C_9	R_10	R_11	R_12	R_13	R_14	R_16	R_17	R_18
1nF	2.2μF	4.7μF	4.7μF	500Ω	1kΩ	1kΩ	1kΩ	1kΩ	1kΩ	10kΩ	10kΩ

The notch frequency is calculated as

$$f_{notch} = \frac{1}{2\pi RC} \tag{5.9}$$

By rearraning it the value of R can be obtained

$$R = \frac{1}{2\pi f_{notch} C} = \frac{1}{2\pi \cdot 90000 \cdot 1n} = 1.77\text{k}\Omega \tag{5.10}$$

The closest value to the calculated one is 1.8kΩ, which gives the notch frequency f_{notch} = 88kHz. The Q factor is tuned using resistor R_{15} where an increased value leads to a decreased Q factor. This resistor is set to 2kΩ after simulation. C_{12} and C_{13} were both chosen as 100nF and R_{21} as 1kΩ. The frequency response is shown in Fig. 5.31.

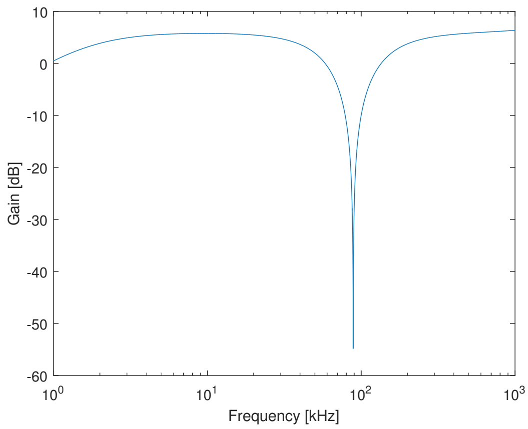

Figure 5.31: Notch filter frequency response

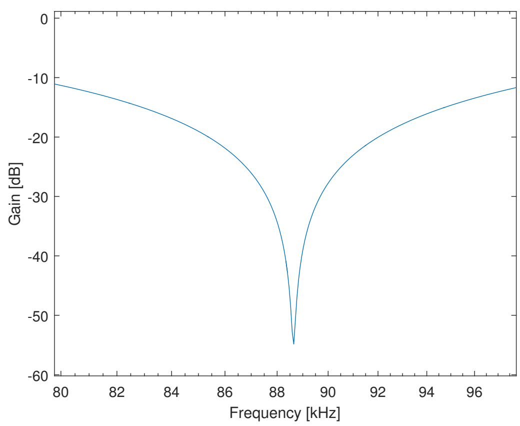

Figure 5.32: Notch filter frequency sweep (zoomed in)

The filter attenuates the notch frequency, 88kHz, by 55dB, while the search coil frequency, 146kHz, is close to 0dB.

5.3.6 Peak detector

The filter output is connected to another peak detector circuit shown in Fig. 5.33.

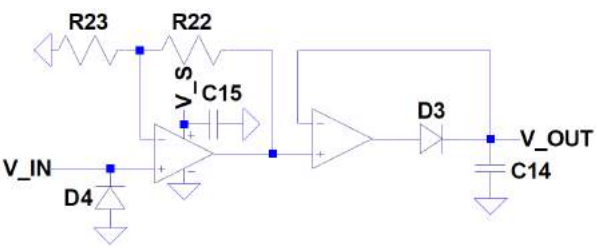

Figure 5.33: Peak detector circuit

It is similar to the peak detector circuit for the ultrasonic receivers - with one exception; it uses a dual version of the operational amplifier instead. With the operating frequency of the conductive objects detection system being 146kHz, the potential maximum amplification using the same operational amplifier as for the ultrasonic receiver peak detectors, the LTC6240 is

$$A_{max} = \frac{GBP}{f} = \frac{18M}{140k} = 123.3 \tag{5.11}$$

At this stage it was assumed that the induction balance would perform well enough to induce less than a 100mV peak at the receiver end with no conductive object present. This gives a potential max amplification of $\frac{5}{0.1} = 50$ before the supply rail is reached, which is below 123.3. However with a better induction balance, more amplification could be possible. It was thus deemed desirable to have more margin. Therefore the dual version of the operational amplifier, the LTC6241 was chosen. It has the same rating as the single version. The only difference is that each package contains two amplifiers. The gain can then be split among the two amplifier circuits, giving a potential maximum amplification of $123.3^2 = 15203$ (123.3 amplification each) which is much more than needed. The amplification is done in the first step with resistor values $R_23 = 1\text{k}\Omega$ and $R_22 = 51\text{k}\Omega$ giving an amplification of $1 + \frac{51}{1} = 52$. The peak detection is done in the second step with $C_14 = 1\mu\text{F}$, the same as for the receiver peak detectors. Decoupling capacitor $C_15 = 100\text{nF}$ and the diodes are N5817 Shottky diodes.

5.4 User and Charging Station alert

To alert the user of a detection two LED's are used, one for each detection subsystem in order to see which system that triggered. Two GPIO (General Purpose Input and Output) pins are used for communication with the charging station, one for each detection subsystem. By default they are both set low and if a detection is made the corresponding GPIO pin is set high which will alert the charging station of detection.

5.5 MCU

The MCU chosen was an Atmega328P-PU from Atmel. It was chosen because it is compatible with an Arduino board. It is also supplied from a 5V supply meaning no additional voltage regulator was required. A pinout schematic can be seen in Fig. 5.34

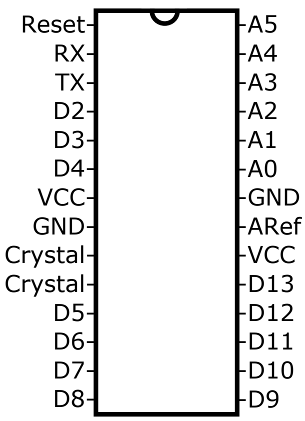

Figure 5.34: Atmel Atmega328P-PU Pinout

It has 14 digital pins. Two of them are used for communication with a computer (RX and TX) and four of them are used by the SPI communication with the external ADC (pins 10-13). The internal ADC has six inputs of which one is used. The MCU uses a on-chip flash memory to store programs. This require a bootloader which is similiar to the BIOS in a computer. The bootloader checks if new code is trying to be uploaded. If it is, the new code is stored in the memory and if not the currently stored code starts executing. The programming was done using Arduino IDE. This requires an Arduino bootloader. The bootloader was installed using an existing Arduino board and online instructions, [15].

5.5.1 TTL

Arduino Boards communicate with the programming computer using TTL, (Transistor Transistor Logic) serial communication. Even though an Arduino Board was not used, the same type of processor and the Arduino IDE was used. Using the same type of communication then meant that no additional work was required for uploading code to the MCU. The actual implementation was done using an USB-to-TTL cable. It has a builtin FT232R chip from FTDI in the USB house which performs the actual data conversion. The connection from the USB connector to the MCU is seen in Fig. 5.35

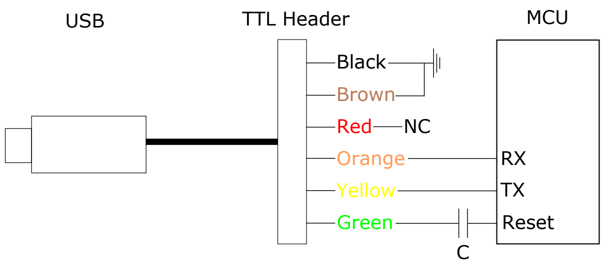

Figure 5.35: USB-to-TTL connector

Black stands for ground and is connected to the board ground. Red is 5V supplied from the USB port. Since the board already have access to 5V this pin is not needed and thus not connected (NC). Orange is used to send data from the computer (transmitter) to the MCU receiver. Yellow is used for the opposite; send data from the MCU (transmitter) to the computer (receiver). Green is called RTS (Request to Send). It is used by the computer before it starts sending information. Since uploading new code requires that the bootloader is running it is connected to the reset pin of the MCU through a 100nF capacitor. When uploading new code the MCU will then be reset so that the bootloader may store the new code. The last signal, brown is called CTS (Clear to Send). It is used to confirm that the receiving unit is ready to receive the data by pulling it low. It is connected to ground making the MCU always ready to receive data when the computer tries to upload new code.

5.5.2 Software Implementation

Fig. 5.36 shows a flowchart of the functionality of the software.

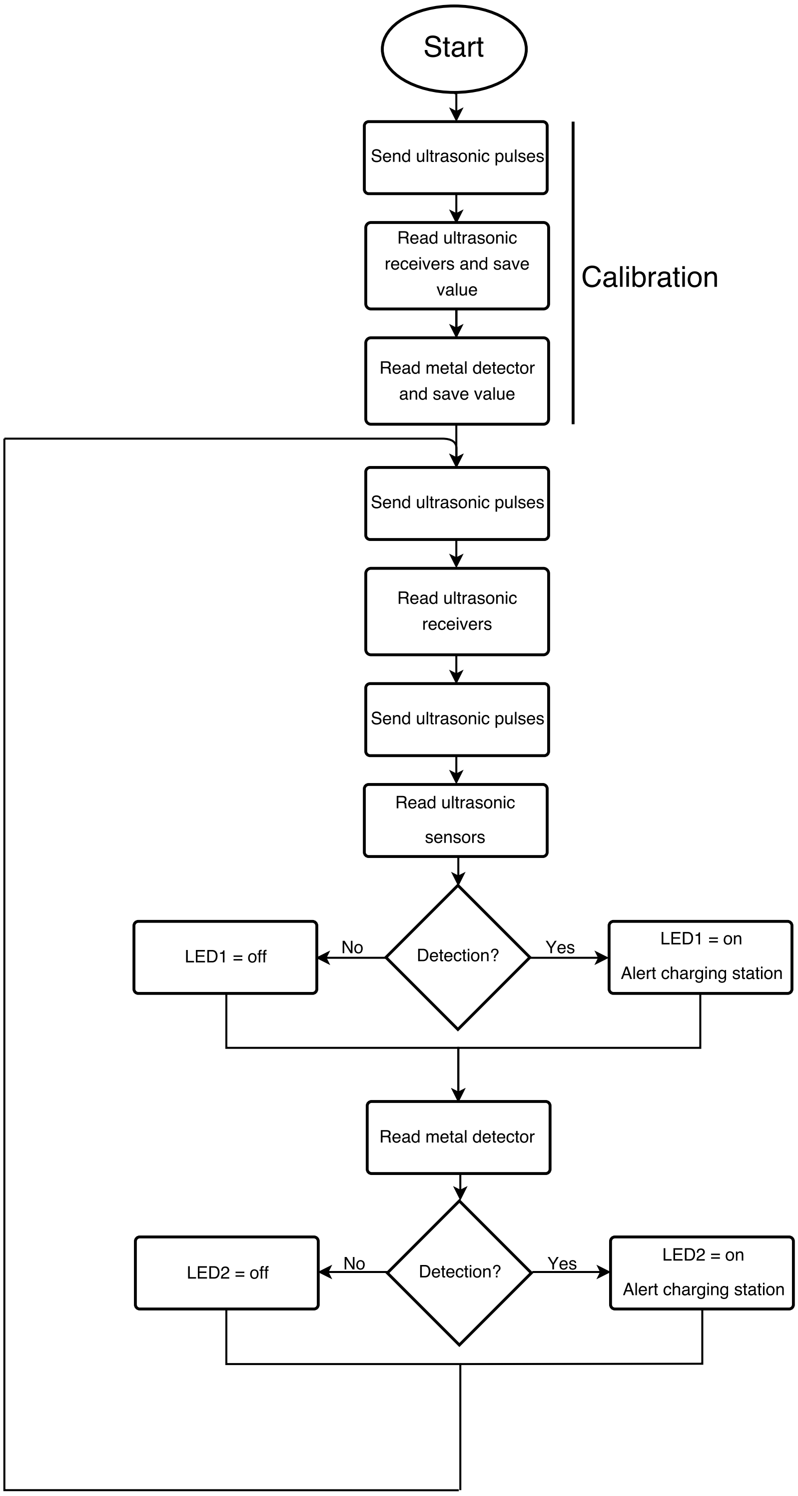

Figure 5.36: Flowchart of the software

When the system is powered up calibration of the conductive objects detector and the ultrasonic tripwires is performed. First 20 samples from the conductive objects detection system is read, and the mean value of those, is saved as the zero level of the metal detector. The same process is then made for the 16 ultrasonic tripwires.

Then the main loop of the program begins. Every loop, the outputs from the conductive objects detector and the receivers are compared with the saved zero levels. The last four differences are summed. If the difference in any case is larger than the threshold, a detection is reported. The ultrasonic distance sensors measure the distance to the closest object. If any object is closer than 170 cm a detection is reported. If a detection is made, one of the LEDs are switched on and on of the GPIO pins are set high depending on which subsystem that registered a detection, ultrasonic or conductive objects.

For testing purposes, the program is able to send data over the TTL cable back to a computer. This in order to make it easier to evaluate the system.

5.6 PCB Layout

With the circuitry design completed and component choice made, a PCB layout was created. On the PCB all components was placed and traces drawn between them. The layout was designed manually using Altium Designer. There exist some general guidelines for designing a PCB layout, for example [14]. However there are no consensus regarding an optimal design and greatly varies from one designer to another. Fig. 5.37-5.40 shows the top and bottom layer of the different PCB's.

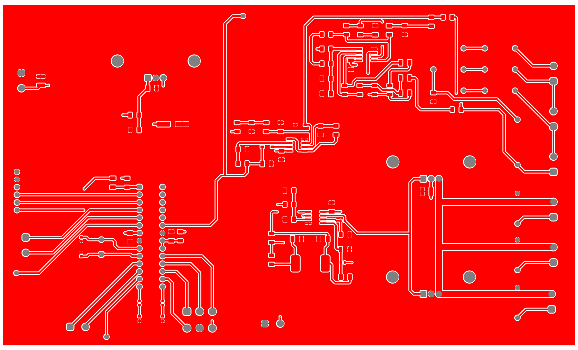

Figure 5.37: Main PCB, top layer

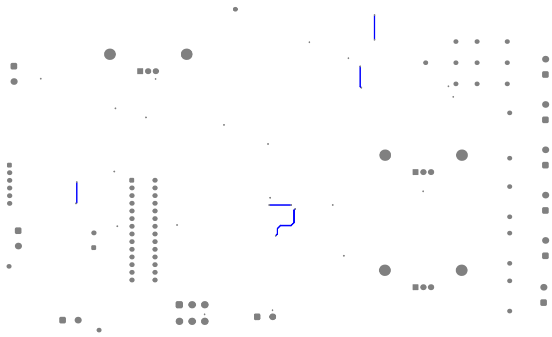

Figure 5.38: Main PCB, bottom layer

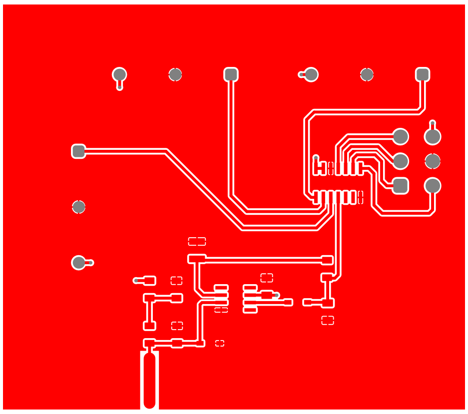

Figure 5.39: External ADC and peak detector top layer

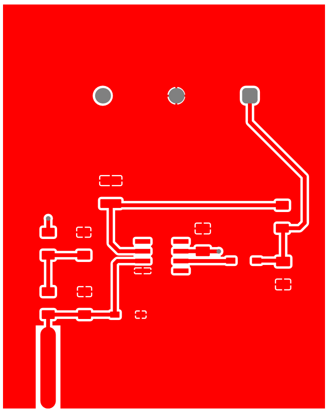

Figure 5.40: Peak detector top layer

These layers are mainly used for signal traces. The top layer is also used as a ground plane. The board also have two inner layers. These are used exclusively as power planes of 5 and 12V respectively.

6

Results

This chapter presents the result and performance of the prototype detection unit.

6.1 Detection of Live Beings

To evaluate the ultrasonic system, a test object was needed. The object was a block of height 7 cm and width 11.7 cm. The ultrasonic system was set up and the object, facing the sensors, was then moved through the area between the ultrasonic receivers and transmitters. The object was moved according to a predefined path, shown in Fig. 6.1. This resulted in three passages through the area of detection and a pause between the passages.

Figure 6.1: Test path for ultrasonic system

The longitudinal distance between the ultrasonic transmitters and the ultrasonic receivers was fixed at 1.9m. The lateral distance between two ultrasonic sensors or two receivers was varied between d = 20cm and d = 40cm. At each time instance it compares the currently read value from the ultrasonic receivers and compare it with the saved value from the calibration. Fig. 6.2-6.4 shows the error between these values at each time instance.

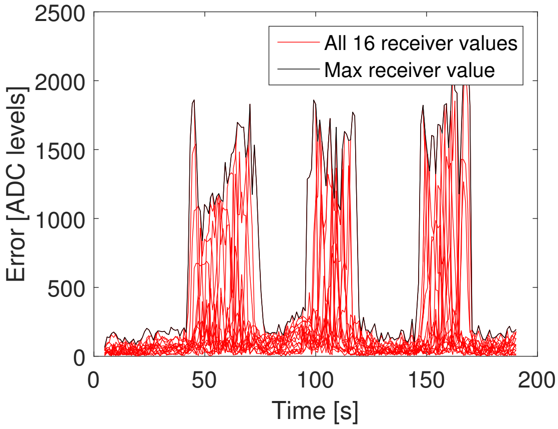

Figure 6.2: Ultrasonic receiver errors with 20 cm lateral distance

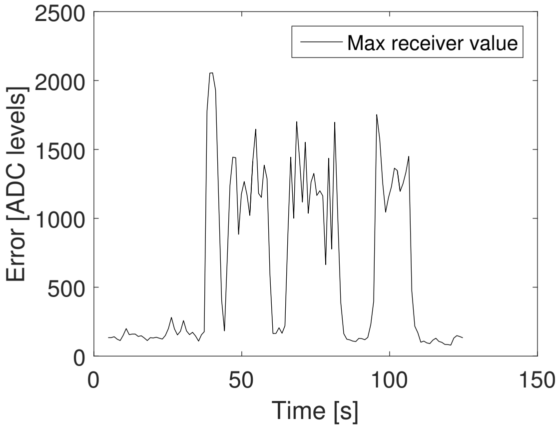

Figure 6.3: Ultrasonic receiver errors with 30 cm lateral distance

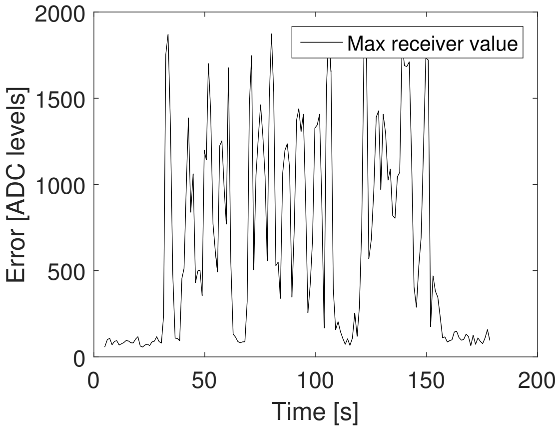

Figure 6.4: Ultrasonic receiver errors with 40 cm lateral distance

In Fig. 6.2 the error from all 16 receiver signals are shown simultaneously. From these 16 values, the signal with the maximum value is chosen at each time instance and compared to a threshold value to determine if a detection is made. Three distinct peaks are obtained, one for each pass through by the object. When the distance d is increased one can observe a drop where the effect the object has on any receiver is small, resulting in a smaller error. The frequency and amplitude of these drops increases with the distance d.

Fig. 6.5-6.7 shows when sensors and the receivers have made a detection. The threshold for the ultrasonic receivers was 400 ADC levels and 170cm for the ultrasonic sensors.

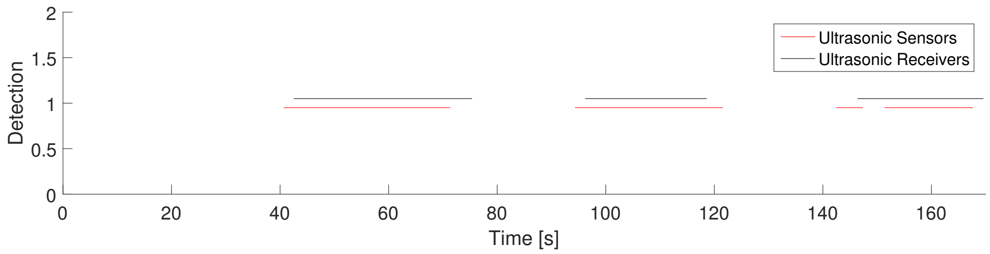

Figure 6.5: Detections made by the ultrasonic sensors and receivers with 20 cm lateral distance

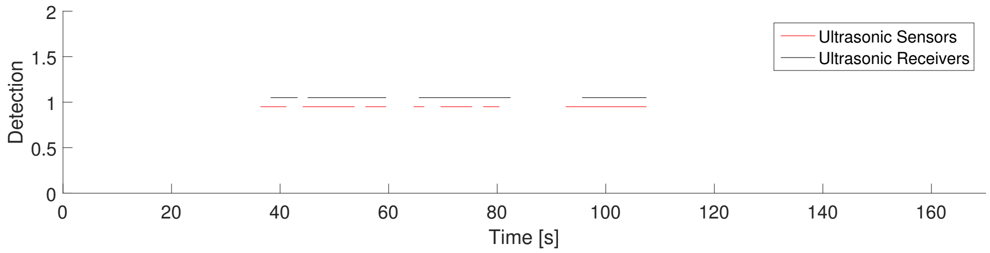

Figure 6.6: Detections made by the ultrasonic sensors and receivers with 30 cm lateral distance

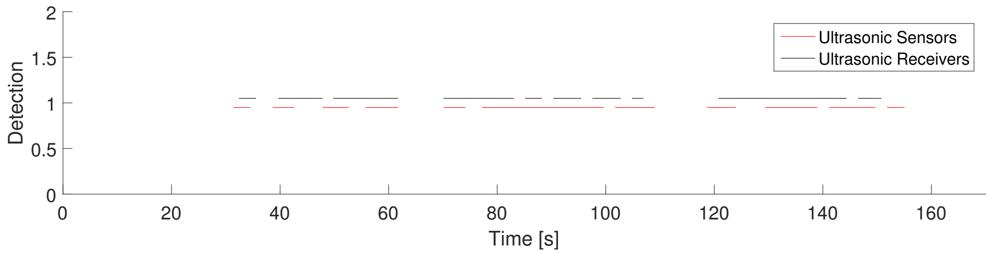

Figure 6.7: Detections made by the ultrasonic sensors and receivers with 40 cm lateral distance

As can be seen some of the drops that were seen in Fig. 6.2-6.4 result in that a detection no longer is made. The ultrasonic sensors also detect the object when it is outside of the area of interest.

6.2 Detection of Conductive Objects

This section presents the results from the detection of conductive objects.

6.2.1 Verification

Before testing was conducted, the outputs from the various stages of the electronics were studied using an oscilloscope and compared to simulation results.

6.2.1.1 Transmitter Side

Fig. 6.8 shows the output from the Colpitts oscillator and the Push-Pull amplifier. Fig. 6.9 shows an FFT of the output.

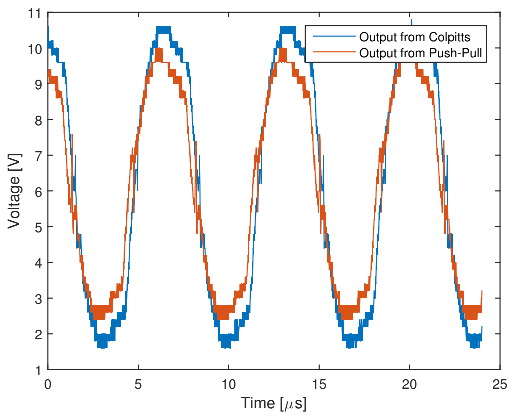

Figure 6.8: Output voltages from Colpitts oscillator and Push-Pull amplifier

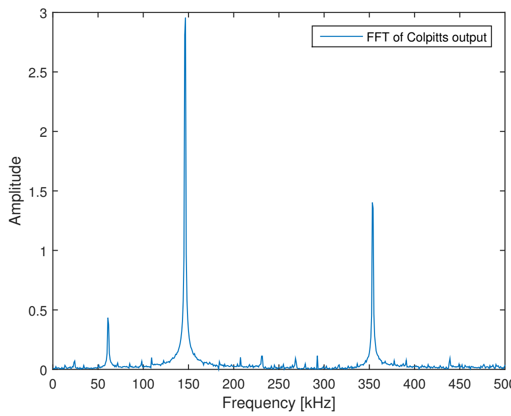

Figure 6.9: Fast Fourier Transform (FFT) of Colpitts output

The output from the Colpitts oscillator and the Push-Pull amplifier is similar to the simulation in the case of amplitude. However the FFT shows that the oscillating frequency is in fact 146kHz rather than 136kHz.

6.2.1.2 Receiver Side

Fig. 6.10 shows the induced signal in the receiver coil as well as the output after the notch filter. Fig. 6.11 shows the output after the amplifier stage and the peak detector output.

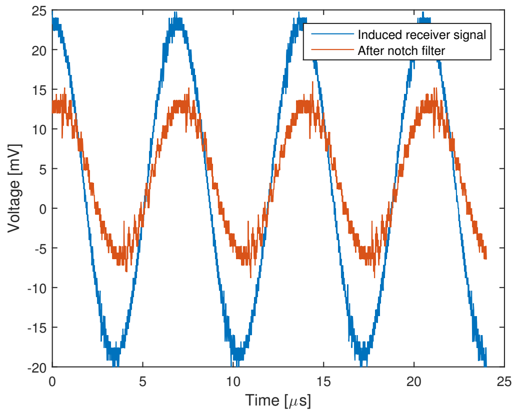

Figure 6.10: Induced signal and notch filter output

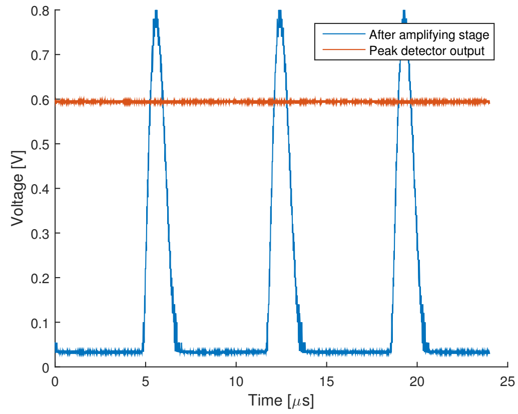

Figure 6.11: Amplification and Peak detector output

A peak of 25mV gets induced in the receiver coil with no conductive object present, meaning the induction balance is not perfect. However, the signal is a smooth sine wave. The notch filter decreased the amplitude to 15mV and also introduced some distortion but the sine wave is still distinguishable. The output from the notch filter is what enters the amplifier. With a peak value of 15mV and an amplification of 52 the output should be 0.78V. This is close to the actual output of 0.8V. Finally the peak detector output is 0.6V which is below the peak value of 0.8 but still expected because of the diode voltage drop.

6.2.2 Current Measurement

In order to determine the current through the transmitter coils, a current measurement probe was connected to the oscilloscope. Fig. 6.12 shows how the current through each transmitter coils when multiple transmitter coils are connected to the same source.

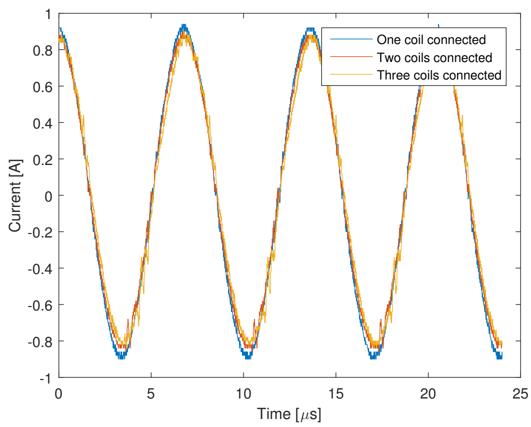

Figure 6.12: Measured current through one transmitter coil with one, two and three connected.

The current is approximately 2A peak-to-peak compared to 2.2A obtained in simulation. One can observe a slight decrease in amplitude when connecting additional transmitter coils but otherwise not much difference. Note that this is the current through only one of the coils. Since the coils are connected in parallel the output from the Push-Pull amplifier will be twice, or thrice, as large when two or three coils are connected.

6.2.3 Test of Search Coil Without Presence of Charge field

For evaluation of the search coil sensors a coin was chosen as test object. As for the ultrasonic system the coin was moved according to a predefined path, first one time at height 8cm and then once again at 2cm with one, two, and three connected coils.

For one coil the setup was done according to Fig. 6.13, yielding the result in Fig 6.14. The 'X' in Fig. 6.13 represents a pause where the coin was held still.

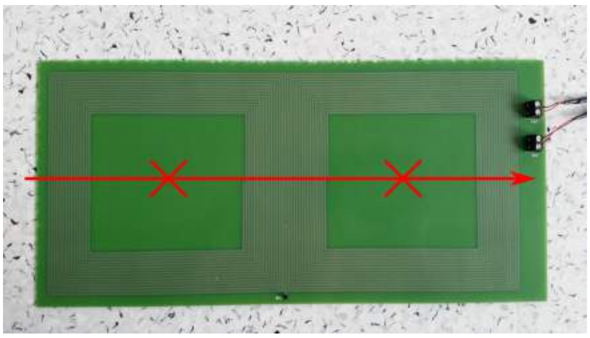

Figure 6.13: Test path for one coil, 'X' indicate a stop

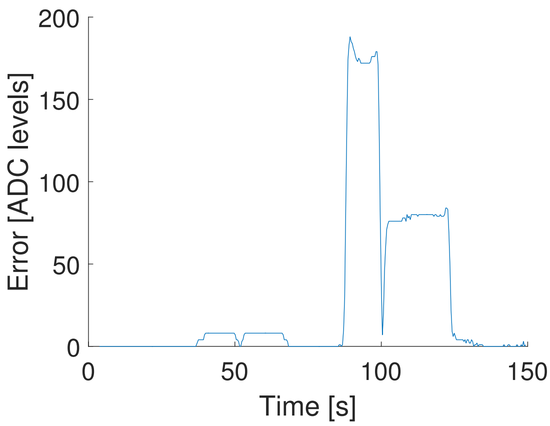

Figure 6.14: Detections made with one coil connected

The calibrated value with no conductive object was 89 ADC levels and Fig 6.14 shows how much the currently read value differs from this value. The coin was moved at 8cm distance approximately between 40-60 seconds. This resulted in two peaks, one each time the coin was held above each half of the coil. Between 90 and 125 seconds the distance was decreased to 2 cm and again two peaks are obtained. This also resulted in much larger amplitudes. However it can be noted that the peaks in this case are of different heights and a larger peak was obtained when the coin was above the left half.

A second coil was then connected and similar tests as before were carried out. In order to test how much the two coils interfere with each other, two different tests were carried out. Firstly, the two coils were placed apart from each other, making them independent. Secondly, the two coils were placed next to each other, which will result in a mutual inductance between the two coils. These setups can be seen in Fig 6.15 and 6.16.

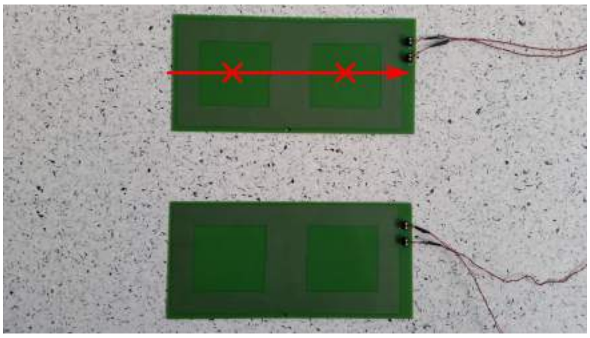

Figure 6.15: Test path for two coils apart, 'X' indicate a stop

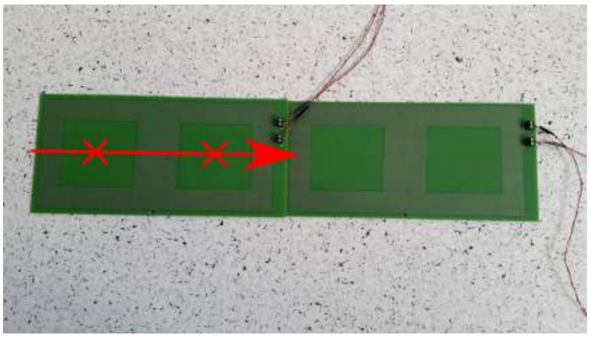

Figure 6.16: Test path for two coils adjacent, 'X' indicate a stop

The result can be seen in Fig 6.17 and 6.18.

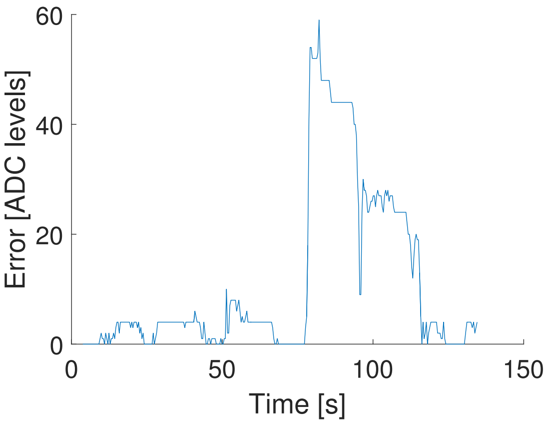

Figure 6.17: Detections made with the two coils apart

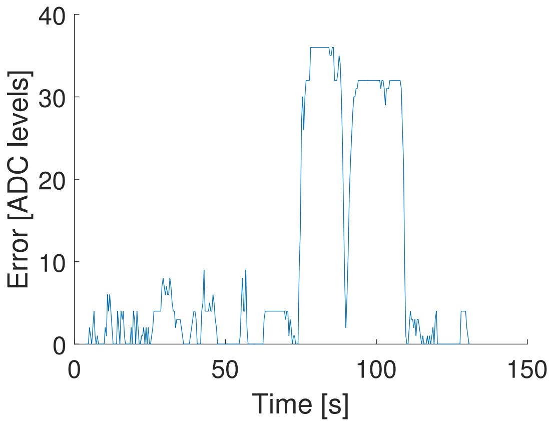

Figure 6.18: Detections made with the two coils adjacent

The calibrated value in this case was 604 ADC levels when apart and 580 ADC levels when adjacent to each other. When compared to the result when using only one coil, a drop in sensitivity can be observed. No distinct peaks are obtained when the coin is at 8cm distance meaning it can no longer be detected. Decreasing the distance to 2 cm gives to peaks, one each time the coin is held above each half. The amplitude has however decreased and is only approximately one third compared to the result when using only one coil. It can also be seen that the amplitude decreases further when the two coils were placed next to each other. Furthermore, the signal has overall more noise.

Finally the same test was done with three connected coils. As for the case with two coils, two setups were tested, one with the coils apart, and one with them adjacent to each other. The setups can be seen in Fig. 6.19 and 6.20.

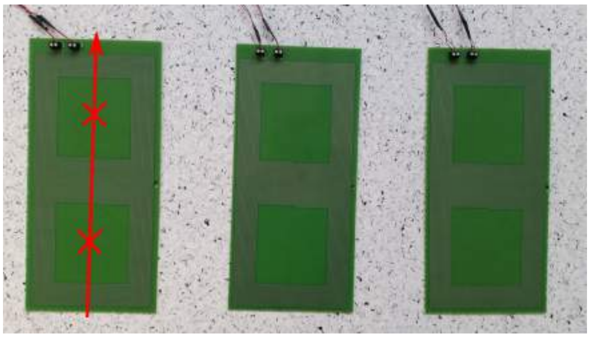

Figure 6.19: Test path for three coils apart, 'X' indicate a stop

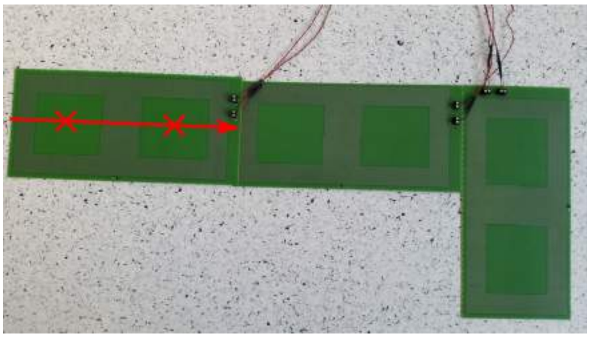

Figure 6.20: Test path for three coils adjacent, 'X' indicate a stop

The result can be seen in Fig 6.21 and 6.22.

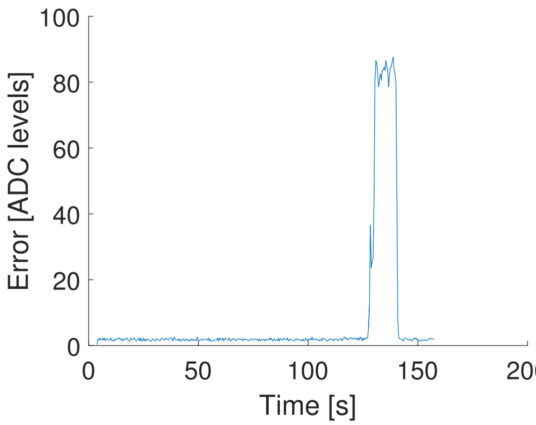

Figure 6.21: Detections made with the three coils apart

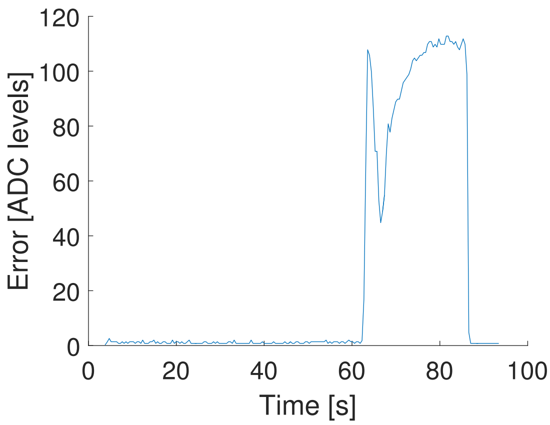

Figure 6.22: Detections made with the three coils adjacent

The calibrated value was in this case 843.65 ADC levels when apart and 843.2 ADC levels when adjacent to each other. Note here that the reason for the decimals in the calibrated values are because they are a mean value of 20 samples. It can be observed that an even larger drop in sensitivity was obtained. Neither coin passages can be detected, indicated by the long flat part in the beginning. To verify whether or not the detection method still worked, the test object was increased. Instead of using only a small coin, a 0.5cm thick sheet of metal was placed 2cm above one of the coil halves. This extra test resulted in the peaks that can be observed in the end. Although this shows that detection of conductive objects still works, the drop in sensitivity is sever.

6.2.4 Test of Search Coil With Presence of Charge field

Finally, a last test was performed together with the charging station. During this test only one search coil sensor was connected. The search coil sensor was placed next to the charging coil. The charging station was then powered on and set to transfer 25W. The detection unit was then powered on and calibrated while the charging station was active. The coin was then placed 2cm away from the search coil sensor. The result can be seen in Fig. 6.23

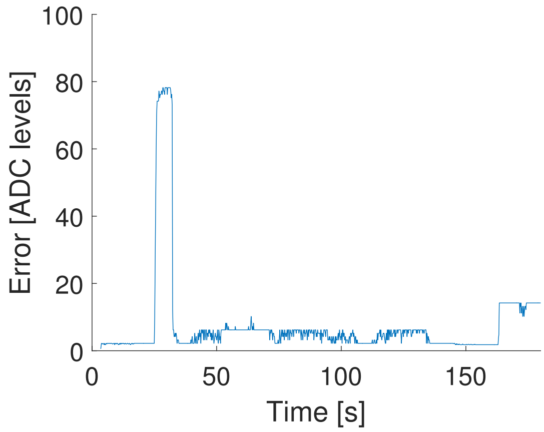

Figure 6.23: Detection in the presence of the charge field

This test resulted in a calibrated value of 116.55 ADC levels. When the coin was introduced after 25 seconds a distinct peak can once again be observed. Between 40 and 135 seconds the transferred effect of the charging station was decreased to 2W which caused an increased error. Between 135 and 160 seconds the transferred effect was again set to 25W, causing the error to decrease. The charging station was then finally shut down completely after 160 seconds.

7

Discussion

The performance of the system and possible improvements are discussed here.

7.1 Detection of Conductive Objects

The search coil sensor system fulfils the specification under some circumstances, specifically how many coils that were used. The system had no problem detecting even small conductive objects as long as only one coil was used. Increasing this number severely reduced the sensitivity.

Having more than one transmitter coil connected to the source in parallel, as in the system constructed during this master thesis, did not affect the performance much. As shown in Fig. 6.12, the current through the coils were fairly consistent when adding more coils, with only some minor decrease in amplitude. This might be because the coils and capacitors do not have the exact same values as specified, because of tolerances. When these values change, it may result in a lower Q factor and a resulting lower current. The maximum number of transmitter coils that can be connected in this way depends on how much output current the Push-Pull amplifier can deliver and the Q-factor of the transmitter coil plus its capacitor. The currently chosen components can deliver 8A peak-to-peak. Also, currently 2A peak-to-peak is obtained in each transmitter coil. This would then result in a maximum number of four transmitter coils. In order to have more transmitter coils, one of several things can be done. Firstly, one can choose other components capable of deliver more current. Secondly, one can use more than one amplifier circuit and have each amplifier circuit serve its own transmitter coils. Thirdly, the properties of the coil itself can be changed in order to lower resistance. Lastly, one can also lower the Q factor of the transmitter coil and its capacitor. This is however not recommended as this would result in decreased sensitivity.

Connecting several receiver coils in series decreased the sensitivity. This is expected, since adding coils in series will increase the total resistance. This, in turn, decreases the Q-factor, and in turn, reduces the current flowing through the coils. The reduced current makes it more difficult to detect an object and smaller objects will not give a large enough current to be detected. This explains the gradually lost sensitivity where a coin could be detected at 8cm with one coil, 2cm with two coils and not at all with three coils. Connecting more than one receiver coil to the same measurement circuit is thus not recommended. The solution to having more than one receiver coil is then to have more measurement circuits, i.e a filter and peak detector circuit. The MCU could then monitor them individually with no resulting loss in sensitivity. Alternatively, a switch might be used to decide which receiver coil that is connected at which time.

Another option would be to increase the sensitivity. This would then make it possible to detect smaller conductive objects. It can be achieved with a larger amplification. The amplification is currently limited by the base voltage, i.e. the voltage when no conductive objects are present. The input voltage to the ADC must not exceed the reference voltage of it or it will break. The internal ADC of the MCU had a maximum rating of 5V. However, an external ADC with a higher voltage rating could have been used. The induction balance also affects how much the signal can be amplified. This is because it is directly related to the base level voltage and the better the induction balance, the lower the base voltage will be.

When the coin was 2cm from the coil, different amplitudes were obtained depending on which half of the coil the coin was above. This may be related to the imperfect induction balance. In one of the halves the coin induced voltage will work in the same direction as the imbalance, meaning their amplitudes will stack, $V_{coin} + V_{imb}$. The resulting error then becomes $V_{coin} + V_{imb} - V_{imb} = V_{coin}$. In the other half the they will instead oppose each other and the amplitude will instead become $|V_{imb} - V_{coin}|$. The resulting error then becomes $||V_{imb} - V_{coin}| - V_{imb}| = |V_{coin}|$ if $V_{imb} \geq V_{coin}$ and $|V_{coin} - 2V_{imb}|$ if $V_{imb} < V_{coin}$. The conclusion of this is that if the coin induced voltage is greater than the base voltage, which may be the case when the coin is close to the coil, the resulting error will be less in one half compared to the other one. In this case it is not a problem since the error is still enough to trigger a detection. However, a situation may occur where the error becomes zero, ($V_{coin} = \frac{1}{2}V_{imb}$). The object would then not be detected. This problem only occurs as a result of only measure the amplitude of the induced voltage. If $V_{imb} < V_{coin}$ the error will be smaller but it will also be phase shifted 180°. If the detection system thus measured both amplitude and phase the phase shift alone could trigger a detection.

Another thing to consider when using multiple search coil sensors is the mutual inductance occurring when they are placed close to each other. As can be seen in Fig. 6.18 the error was decreased when the coils were close to each other. This is because the mutual inductance cause the Q-factor to decrease and the resulting drop in sensitivity. The tuning of the resonance circuits were done assuming the coils were independent from each other. As this was not the case, this can easily be solved by instead measuring the inductance when the coils are adjacent and use that inductance when tuning the resonance circuits instead.

7.1.1 Colpitts Oscillator

According to theory, the operating frequency of the Colpitts Oscillator should have been 136kHz. However, in the constructed system this was not case. Instead the frequency was 146kHz. This can be explained by the fact that the components have some stray capacitance, and that the components are non-ideal. The capacitances used in the LC circuit of the Colpitts Oscillator had a tolerance of 10%, while the inductances had a tolerance of 20%. This gives a potential frequency swing between 119-160kHz. A finished product, ready for manufacturing, could use components with lower tolerances to decrease this frequency range. The resonance circuits need to be tuned to the resonance frequency. To achieve this, there are two alternatives. Firstly, components with lower tolerances could be chosen. Secondly, the output from the oscillator could be measured in order to tune every resonance circuit individually.

Since the resonance circuits should be tuned to this frequency, either components with very low tolerance would have to be used, or the output from the oscillator would have to be measured in order to perform individual tuning.

7.1.2 Performance close to the inductive charger

The test with the detection unit together with the inductive charger was done in order to see if interference from the charging field will cause any problem to the electronics board or the search coil sensor. It was also done to test the performance of the filter. It should be noted here that there is a large difference between the power transfer being 25W, as in the test, or 3000W, as in full strength, but it can still give an indication of its performance. The test showed that the sensitivity was not affected much by the charging station. The coin was placed in front of the receiver half corresponding to the fourth peak in Fig. 6.14 which were carried out without the charging station. The amplitudes are then very similar, approximately 80 ADC levels. The largest difference was that the base level voltage changed from 89 to 116.55 ADC levels. This means that the filter is not perfect. The filter was not tuned as good as it could have been, which can have a large impact on performance. The error changed when the effect of the charging station was changed. This can be problematic for several reasons. First, depending one how stable the power transfer will be, it can be more difficult to detect small objects as the threshold must be set higher to counter variations in the power transfer. Secondly it becomes a problem when an object has been detected and the charging station turns off. A study can be done here to see if the impact varies between runs. If it does not it can be implemented as a constant and accounted for. If it does, a recalibration may be needed after a detection is made and then again when restarting. The charging station did not seem to have an affect on the electronics board at a distance of 40 cm.

7.2 Detection of Live Beings

The system for detecting live beings performed overall very well and the method should be applicable in a commercial product. The biggest advantage is that, as long as the sensor density is high enough, no objects will be missed. The biggest downside is that the system can not distinguish between different kinds of objects and all objects of a large enough size will be detected, not only live beings. This was known when designing the system and was considered an acceptable downside as the area under the car is mostly free of objects anyway. Another downside is that if an object is placed vary close to one of the transmitters or receivers it will give a large error even if the object is small. This could lead to unwanted detections.

By studying Fig. 6.2-6.4 and Fig. 6.5-6.7 the effect of increasing the lateral distance between the sensors can be seen. When the distance is 20cm, the error is well above the threshold of 400 ADC levels at all times when the object is in the area of interest. When starting to increase the distance, gaps starts to appear where the object gets missed. This is seen in the sudden drops in the error. The more the lateral distance is increased, the more frequent these drops happen, and with a larger amplitude. When these drops is large enough to take the error below 400 ADC levels, the object gets missed. The reason for why these gaps occur can be related to Fig. 4.2. Even at 20cm lateral distance there are blind spots in the detection area. They are just small enough so that the test object, which were set as minimum size to detect, does not fit in these blind spots. When the distance increases, the size of these blind spots increase as well. This then makes it possible for the object to be missed.

It can also be noted that the use of ultrasonic distance sensors appear to be largely unnecessary. Only when the lateral distance was 40 cm, in Fig.6.7, did the distance sensors detect the object while the tripwires did not. They are also overall more unreliable which can be seen in Fig. 6.5-6.7 where gaps in the detection occur more frequent for the ultrasonic sensors than for the tripwires. This is because the performance of a ultrasonic sensor is dependent on the size and shape of the object. The further away the object is, the larger it needs to be. It must also not absorb the ultrasonic pulses, nor deflect them for the sensors to receive the echo. Another problem with the sensors were that they sometimes detected the object when it was outside the area of detection which is seen in Fig. 6.5-6.7 where the detections for the sensors starts/ends before/after the receivers. Since they also add both cost and complexity to the system, their use can not be truly motivated. However, they could possibly be regarded as an extra layer of redundancy.

Before the system will be ready for a commercial product, issues that were considered to be outside the scope of this project must be solved. Namely, weather and impact resistance. Some general ideas for solutions are found in Section 4.1.1, but these will require further development.

One last thing to consider is the presence of the inductive charger. The magnetic field generated by the charger can interfere with the electronics. This did not seem to cause any trouble for the electronics when the conductive objects sub-system was tested together with the charging station. Since the ultrasonic receivers and sensors will be placed further away from the charging station this should not be a problem, although this has not been tested.

8
Conclusion

A prototype of a detection unit has been developed, constructed and evaluated. It is capable of detecting live beings, as well as conductive objects. The area of application is together with an inductive charger and its purpose is to detect if live beings or conductive objects are too close to the inductive charger. The detection unit consists of two subsystems, one for each type of object. For live beings, ultrasonic sensors and ultrasonic receivers was used. The sensors measure the distance to the closest object and the receivers act as tripwires and detect a blocking object. Four sensors and four receivers were placed on opposite sides of the detection area - approximately 1.9 meters apart. The lateral gap between two sensors (and receivers) were varied between 20 and 40cm covering an area of 1.9x0.6 to 1.9x1.2 meters. Four sensors and receivers were enough to detect an 11cm wide object in the detection area. However, it was shown that blind spots appears when the gap between the transmitters and receivers is too large.

Search coil sensors utilizing induction balance was used to detect conductive objects. The operating frequency was 146kHz. This is high enough to minimize interference with the operating frequency of approximately 90kHz of the charging station. The sensors had no problem detecting a coin-sized object at 8 cm height, although sensitivity dropped quickly when connecting multiple sensors in series. The sensors still functioned well in close proximity to the charging station, while the station was transferring on low power.

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A

Appendix 1

Code for the MCU.

```
#define US1 2        // Ultrasonic Sensor 1
#define US2 3        // Ultrasonic Sensor 2
#define US3 5        // Ultrasonic Sensor 3
#define US4 6        // Ultrasonic Sensor 4
#define SELPIN 10    // SPI Selection Pin
#define MOSI 11      // SPI MOSI
#define MISO 12      // SPI MISO
#define SPICLOCK 13  // SPI Clock
#define CALNUM 20    // Number of data points for calibration
#define MEANNUM 5    // Number of data points for detection
#define LED1 8       // LED to indicate live being detected
#define LED2 9       // LED to indicate metal detected
#define LBGPIO 4     // GPIO to inducate live being detected
#define METALGPIO 7  // GPIO to indicate metal detected
#define METDETPIN A0// Metal detector input

/////////////////////////////////
/////General Varibles///////////
/////////////////////////////////
int val;
unsigned long timeStamp;

/////////////////////////////////
///Metal Detector Variables//////
/////////////////////////////////
double metalSensorValue;
double metalAvg;
double metalError[MEANNUM];
double metal_cummulative_error;

/////////////////////////////////
////Ultrasonic Variables/////////
/////////////////////////////////

//Tripwires
int readvalue1;
int readvalue2;
int readvalue3;
int readvalue4;
double US_averages[16];
```

```
double US_cummulative_error[16];
double US_error[16][MEANNUM];

//Distance Sensors
double US_D_detected[4];

////////////////////////////////
///Calibration and setup////////
////////////////////////////////

void setup() {

 pinMode(SELPIN, OUTPUT);
 pinMode(MOSI, OUTPUT);
 pinMode(MISO, INPUT);
 pinMode(SPICLOCK, OUTPUT);
 pinMode(LED1, OUTPUT);
 pinMode(LED2, OUTPUT);
 pinMode(LBGPIO, OUTPUT);
 pinMode(METALGPIO, OUTPUT);

 digitalWrite(SELPIN,HIGH);
 digitalWrite(MOSI,LOW);
 digitalWrite(SPICLOCK,LOW);
 digitalWrite(LED1,LOW);
 digitalWrite(LED2,LOW);
 digitalWrite(LBGPIO,LOW);
 digitalWrite(METALGPIO,LOW);

 Serial.begin(9600);
 delay(500);

 calibration();
}

void calibration(){
  // Calibrate both sensor systems and flash lights when done

 for (int i=0; i < CALNUM; i++){
     tripwires_read(US1);
     store_US_averages(0);
     delay(20);
     tripwires_read(US2);
     store_US_averages(4);
     delay(20);
     tripwires_read(US3);
     store_US_averages(8);
     delay(20);
     tripwires_read(US4);
     store_US_averages(12);
     delay(20);
```

```
    metalAvg = metalAvg + analogRead(METDETPIN);
  }
  metalAvg = metalAvg/CALNUM;
  Serial.println(metalAvg);

  for (int i=0; i < 3; i++){
    digitalWrite(LED1,HIGH);
    digitalWrite(LED2,LOW);
    delay(100);
    digitalWrite(LED1,LOW);
    digitalWrite(LED2,HIGH);
    delay(100);
  }
  digitalWrite(LED2,LOW);
}

void store_US_averages(int offset){
  // Store averages for ultrasonic receivers
  US_averages[0+offset] = US_averages[0+offset]+readvalue1/CALNUM;
  US_averages[1+offset] = US_averages[1+offset]+readvalue2/CALNUM;
  US_averages[2+offset] = US_averages[2+offset]+readvalue3/CALNUM;
  US_averages[3+offset] = US_averages[3+offset]+readvalue4/CALNUM;
}

void store_US_error(int offset_x,int offset_y){
  // Store error for ultrasonic receivers
  US_error[0+offset_x][offset_y] = abs(readvalue1-US_averages[0+offset_x]);
  US_error[1+offset_x][offset_y] = abs(readvalue2-US_averages[1+offset_x]);
  US_error[2+offset_x][offset_y] = abs(readvalue3-US_averages[2+offset_x]);
  US_error[3+offset_x][offset_y] = abs(readvalue4-US_averages[3+offset_x]);
}

void update_cumulative_error(int index){
  // Calculate cummulatice error for ultrasonic receivers
  for (int i=0; i < 16; i++){
    US_cummulative_error[i] = US_cummulative_error[i]+US_error[i][index]-US_error[i][(index+1) % MEANNUM];
  }
}

double getMaximumValue(double* array, int size){
  // Return maximum value of array
  int maxIndex = 0;
  double max = array[maxIndex];
  for (int i=1; i<size; i++){
    if (max<array[i]){
      max = array[i];
      maxIndex = i;
```

```
    }
  }
  return max;
}


int read_adc(int channel)
// Read external ADC
{
  int adcvalue = 0;
  byte commandbits = B11000000;          // Command bits - start, mode, chn (3), dont care (3)

  //allow channel selection
  commandbits|=((channel-1)<<3);

  digitalWrite(SELPIN,LOW);              //Set ADC active
  for (int i=7; i>=3; i--)
  {
    digitalWrite(MOSI,commandbits&1<<i);
    digitalWrite(SPICLOCK,HIGH);
    digitalWrite(SPICLOCK,LOW);
  }

  digitalWrite(SPICLOCK,HIGH);           // Ignores 2 null bits
  digitalWrite(SPICLOCK,LOW);
  digitalWrite(SPICLOCK,HIGH);
  digitalWrite(SPICLOCK,LOW);


  for (int i=11; i>=0; i--)              // Read ADC value
  {
    adcvalue+=digitalRead(MISO)<<i;
    digitalWrite(SPICLOCK,HIGH);
    digitalWrite(SPICLOCK,LOW);
  }
  digitalWrite(SELPIN, HIGH);            // Set ADC inactive
  return adcvalue;
}

long ultrasonic_read(int pin)
// Read ultrasonic distance sensor and return distance in cm
{
  long duration, distance;
  pinMode(pin, OUTPUT);
  digitalWrite(pin, HIGH);
  delayMicroseconds(2);
  digitalWrite(pin, LOW);
  pinMode(pin, INPUT);
  duration = pulseIn(pin, HIGH);
  distance = 0.017*duration;
  return distance;
```

```
}

void update_US_D_detection(long distance, int index){
  if(distance != 0 && distance < 170 && US_D_detected[index]!=6){ //cm eller meter?
      US_D_detected[index] = US_D_detected[index] + 1;
    }
    else if((distance == 0 || distance > 170) && US_D_detected[index]!=0){
      US_D_detected[index] = US_D_detected[index] - 1;
    }
}

void tripwires_read(int pin)
// Read ultrasonic receivers
{
  pinMode(pin, OUTPUT);
  digitalWrite(pin, HIGH);
  delayMicroseconds(2); // Added this line
  digitalWrite(pin, LOW);
  delay(8);
  readvalue1=read_adc(1);
  readvalue2=read_adc(2);
  readvalue3=read_adc(3);
  readvalue4=read_adc(4);
}

void loop()
// Main loop
{
  long distance;

  for (int index=0; index < MEANNUM; index++)     // Read ultrasonic receivers, sensors and metal detector and save mean value
  {
    delay(5);
    tripwires_read(US1);
    store_US_error(0,index);
    delay(5);

    tripwires_read(US2);
    store_US_error(4,index);
    delay(5);

    tripwires_read(US3);
    store_US_error(8,index);
    delay(5);

    tripwires_read(US4);
    store_US_error(12,index);
    delay(5);

    update_cumulative_error(index);
```

```
    distance = ultrasonic_read(US1);
    delay(5);
    update_US_D_detection(distance, 0);
    distance = ultrasonic_read(US2);
    delay(5);
    update_US_D_detection(distance, 1);
    distance = ultrasonic_read(US3);
    delay(5);
    update_US_D_detection(distance, 2);
    distance = ultrasonic_read(US4);
    delay(5);
    update_US_D_detection(distance, 3);

    if((400<getMaximumValue(US_cummulative_error,16)) || (2<
getMaximumValue(US_D_detected,4)))     // Trigger ultrasonic subsystem?
    {
      digitalWrite(LED1,HIGH);
      digitalWrite(LBGPIO,HIGH);
    }
    else
    {
      digitalWrite(LED1,LOW);
      digitalWrite(LBGPIO,LOW);
    }

    metalSensorValue = analogRead(METDETPIN);
    metalError[index] = abs(metalSensorValue-metalAvg);
    metal_cummulative_error = metal_cummulative_error+metalError[index]-
metalError[(index+1) % MEANNUM];

    if(metal_cummulative_error > 10)
                                  // Trigger metal subsystem?
    {
      digitalWrite(LED2,HIGH);
      digitalWrite(METALGPIO,HIGH);
    }
    else
    {
      digitalWrite(LED2,LOW);
      digitalWrite(METALGPIO,LOW);
    }
    ////////////////////////////////
    ////Check for communication from matlab
    ////////////////////////////////

    if (Serial.available() > 0)
    {
      val = Serial.read();
      if (val == 'M')                              // Conductive objects
detector
```

```
        {
          Serial.println(metal_cummulative_error);
        }
        else if(val == 'T')                               // Time
        {
          timeStamp = micros();
          Serial.println(timeStamp);
        }
        else if(val == 'R')                               // Ultrasonic receivers
        {
          for (int i=0; i < 16; i++){
            Serial.println(US_cummulative_error[i],DEC);
          }
        }
        else if(val == 'D')                               // Ultrasonic sensors
        {
          for (int i=0;i<4;i++)
          {
          Serial.println(US_D_detected[i]);
          }
        }
        else if(val == 'A')                               // Averages
        {
          for(int i = 0;i < 16;i++)
          {
            Serial.println(US_averages[i],DEC);
          }
        }
      }
    }
}
```