Design and Testing of Magnetic Torquers for Pico Satellite Attitude Control

MSc Thesis

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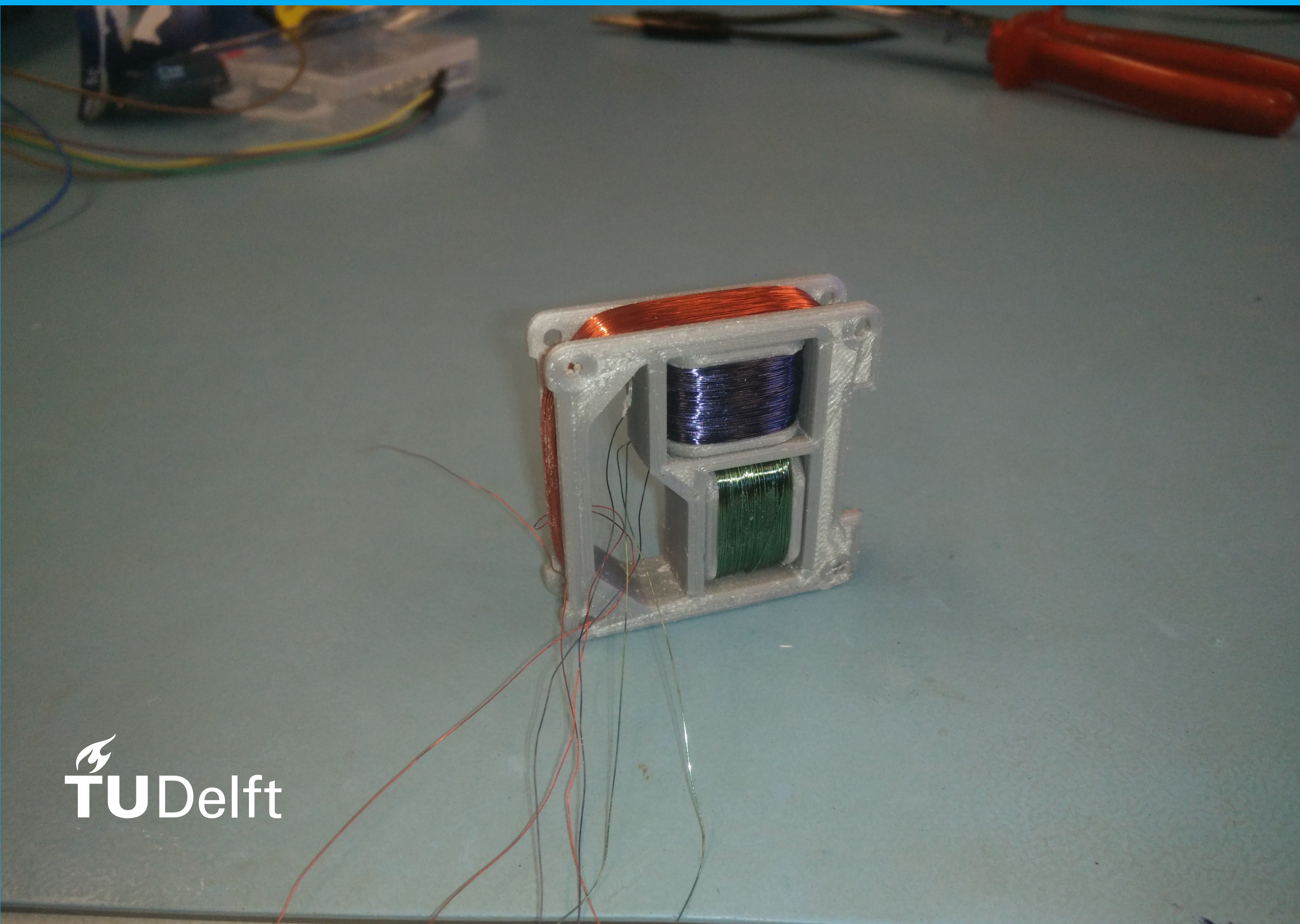

TU Delft

Design and Testing of Magnetic Torquers for Pico Satellite Attitude Control

Electric Magnetic Torquers for Delfi PocketQube Satellites

by

M.F. van den Bos

to obtain the degree of Master of Science,
at the Delft University of Technology,
to be defended publicly on July 25, 2019 at 13:30.

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TU Delft

Preface

As child I was always fascinated by building things, and a long time ago, I decided I would become an engineer! During the thesis work I struggled but thankfully the support from a lot of people made it possible to progress far enough to present to you this report.

When the idea for this thesis was first presented to me by Jasper Bouwmeester I almost immediately decided that this was a good thesis for me. It was however the support and encouragement from Stefano Speretta that allowed me to make it a real thesis project. I am therefore especially grateful to Stefano, but also to Sevket and the rest of the Space Systems Engineering group that made it possible for me to pursue this research project.

Furthermore, I would like to thank Pauline for her patience, my family for their endless support in many ways, and my friends who encouraged me to keep going.

Glossary

A copy of this glossary can be found in the appendix for easy access.

A :	Area, quantity with unit $[m^2]$
A :	Amperé, SI base unit of electrical current
ADCS :	Attitude Determination and Control System
Am^2 :	Amperé meter squared (unit of magnetic moment)
AWG :	American Wire Gauge
COTS :	Commercial of the shelf
CubeSat :	nano satellite adhering to CubeSat standard
d :	arbitrary distance
Delfi-PQ :	pico satellite from TU Delft
I :	electrical current
I2C :	I^2C is a common serial communication protocol
kg :	kilogram, SI base unit of mass
m :	meter, SI base unit of length
mG :	milliGauss, unit of magnetic field density where 1 $mG = 1 \cdot 10^{-7} T$
nano satellite :	satellite of mass less than 10 kg
p :	unit of size PocketQube
PCB :	Printed Circuit Board
pico satellite :	satellite with mass less than 1 kg
PocketQube :	pico satellite adhering to PocketQube standard
R :	radius
rho :	resistivity
s :	second, SI base unit of time
SPI:	simple serial communication protocol
T :	Tesla, Unit of magnetic field density$[Wb/m^2]$
U :	unit of size CubeSat
V :	Voltage, or electric potential
$[V]$:	Volt unit $[m^2 kg s^{-3} A^{-1}]$
Wb :	Unit of magnetic flux $[m^2 kg s^{-2} A^{-1}]$

PCB nomenclature	
blind via:	a connection between adjacent layers, but not all layers. blind vias are more expensive than vias.
inner layer:	a layer inside the PCB no components can be placed on this layer
layers:	the number of copper planes in a PCB. A PCB typically has an even number of layers. The more layers a PCB has, the more complex the circuit can be.
outer layer:	layer on the outside of the PCB. Surface mounted components can be placed here.
PCB:	**P**rinted **C**ircuit **B**oard, a circuit that is 'printed' on substrate material.
plane:	a synonym for layer. Typically used if a layer is used for a single purpose. e.g. a ground plane means a layer that is entirely used as a ground.
Stitching via:	A redundant via that is placed to ensure good conduction between different layers to avoid thermal stress and voltage differences due to long current paths.
thermal:	A reduction in copper area to reduce thermal conduction, for easier soldering.
trace width:	the width of a current path. The trace width determines the resistance of the trace. Traces are created by covering the entire substrate in copper and then etching away the copper between the traces. Therefore all traces in a single layer have the same copper thickness.
trace:	a current path on a PCB, formed by etching away some of the copper of the layer.
via:	a connection between all layers of a PCB.
pad:	a exposed copper surface where using solder a connection can be made with a surface mounted component.
soldermask	area of a PCB where the copper is covered in a layer that prevents adhesion of solder.

Abstract

The topic of the research is magnetic attitude control. This project is done as part of the Delfi-PQ satellite program. The faculty of Aerospace engineering intends to launch a family of PocketQube satellites with ever increasing complexity. The first satellite will be Delfi-PQ. In order to stabilize the satellites attitude, for performance communications, power generation, and possible payloads, an attitude control system is required. In order to generate an external torque a magnetic attitude control system is necessary.

Existing solutions for CubeSats are not designed for a satellite as small as Delfi-PQ. The satellite has very limited electrical power. This is the main limitation to the magnetic attitude system, because in order to create a magnetic field large electrical currents are used. Therefore the primary external question is to create a system that uses little electrical power.

In a literature study the state of the art of magnetic sensors was examined. Also a brief examination of the current options for magnetic actuation is made and it is explored if a science mission would be a possibility. Based on literature it is concluded that in order to get useful science data the satellite is currently not capable enough.
Furthermore it has been realized that only a few articles have been written on the actuators of a magnetic control system.

The external objective is to provide a low power attitude control system. Based on the literature study there are many ways in which this objective can be met. For example the actuators can be improved so that they consume less power. Alternatively the sensors may be improved to reduce attitude errors. Improvement could be made to the control algorithms to reduce the required torque. Or the entire actuator architecture can be altered improving the efficiency of the system as a whole.

The last option is chosen for this research project. This choice is made because this is one of the most promising options for improvement, and because it best aligns with the competencies of the researcher.
Therefore the research question will be: Which is the most advantageous magnetic attitude control system for reducing angular rates of a PocketQube?

Attitude control system, means in this context the hardware part of the system. The total system consists of both the hard and software. The hardware itself is challenging to build and design, especially within the limits of a PocketQube. This thesis is therefore focused on the hardware. The control software for a magnetic attitude control can either be quite simple or really complex. As long as the system is tasked to reduce the angular rotation rate of the satellite the software is relatively simple. When the system is tasked to point the satellite the attitude control software becomes really complex. The hardware, for both pointing and stabilization is (mostly) the same however.

The methodology chosen is using a case studies, testing and comparing several hardware systems. Because it is a case study it is not possible to test every possible configuration. Only a few system configurations can be tested. It is the intention to give a qualitative answer to the question which system will be best based on the experience with several systems.

One of the sub questions for this research proposal is "Can the hardware be tested accurately?". An accurate test will help determine which system performs best. It is difficult to compare test results from different systems if the test results are not reliable. In addition to that testing magnetorquers is also very challenging to do accurately.

It is chosen to focus solely on active attitude control. This choice was made by the DelFi-PQ project team. The reasons for this choice are related to development cost and to give room for improvement. The program also includes research in micro propulsion. In order to use a propulsion, active attitude control is preferable,

even though Delfi-PQ itself has no propulsion module.

A magnetorquer generates a torque equal to the cross product of a magnetic moment of the torquer and the ambient magnetic field. A magnetorquer is built out of a number of current loops. Integrating Faradays law over a current loop will yield its magnetic moment which is denoted by μ. This moment can be amplified by placing in the interior of the current loop being of a material with high magnetic permeability. In general, the integral will simplify to $\mu = \mu_r \cdot I \cdot A \cdot N$. In this formula μ is the magnetic moment, μ_r is the relative permeability of the core, I is the current in the coil, A is the internal area inside the loop and N is the number of loops. When placing a number of current loops in the same orientation their magnetic moments can be added together.

As input to the control software it is important to find a parameter n which is the magnetic moment divided by the current. When n is known the control software can select a torque by controlling the (average) current. There are two ways to find this parameter n. It can be found by calculation or by testing. It would seem that the calculation is very simple, namely, $n = \mu_r \cdot A \cdot N$ However there are some difficulties. For example the parameter μ_r is a material property, but the shape of the material also has an influence on the effective parameter. Another issue is the area A. This area has to be known very accurately to arrive at a good estimation of n. However for a coil created out of copper winding, the area is determined by the location and shape of the copper wire. This is determined by construction quality.

For that reason it is good to also test the coils once they are built. Both to confirm the accuracy of the calculations and to incorporate any deviations from the model created by imperfect construction. In order to speed up production of Delfi-PQ, the decision was made to only consider wire wound air coil magnetorquers for this first satellite. The design and optimization of this magnetorquer system was done as part of this thesis. The most important parameter is power consumption. That this is important was given by the project leader. However speed and reliability of construction are also very important, as is volume. Therefore some of the design choices moved away from a system with higher power efficiency to a design that is easier to construct. Within the choices made to ease construction the goal of optimization of the first design was to maximize the magnetic moment as a function of the power expended.

Since one of the most important parameters is the power usage of the system, it is important to reduce the electrical resistance of the magnetorquer as much as possible, while maximizing the parameter n. The key here is that the given volume must be utilized in such a way that all different requirements can be met. In order to maximize efficiency, the resistance has to be as low as possible, and the area of the loop as large as possible. The largest area inside a rectangular volume is a rectangular coil, however the bending radius of the wire cannot be too small or else it will break.

Also, in order to create a torque around each axis three coils are required. Because three coils have to fit in the volume and they have to be placed orthogonal, increasing the size of one coil would reduce the size of another. Furthermore, it was given the satellite power system operates at 3.3 Volt. However, that would mean that the resistance of the coil would have to be increased otherwise the power would increase to much. This would mean that the efficiency was unfavourably low. It was therefore decided to use a switching converter to reduce the voltage in the coil. This is because the current needs to be large, and the power determined by the voltage multiplied by the current. Therefore a low voltage is desirable.

In the end a system was designed that could meet all requirements. It is close to the best system that could be designed for the given requirements, within the available volume, using copper wire and no ferromagnetic materials. The construction of the system relies on the use of a 3D printer. In order to be able to construct it, the margins in the design had to be increased slightly.

One of the requirements for Delfi-PQ is that, the system has to be stand alone, in order not to interfere with the design of other subsystems of the satellite. However, if the system could be integrated the with other subsystems many more possibilities open up, and other systems can be designed that could be much more power efficient.

In order to answer the research question, other options for magnetic torquers are also explored. Since a torquer requires a current loop and the satellite is built out of PCB's (printed circuit boards), a logical solution is to incorporate current loops in the PCB's of the satellite. Fortunately, structure of the satellite walls is formed by a PCB. Therefore, there are PCB's available in three orthogonal planes. If all PCB's are in the same plane this plan would not work.

This concept is further developed in the thesis. A PCB with a coil inside was designed, and produced. The PCB also included a switching converter. In order to design the PCB a script was written that lays out the coil on the PCB. This way the parameters of the coil can easily be changed to optimize it. The switching converter was not part of the thesis but since it is important to the performance of the system it was decided to design the system including a switching converter. This concept was thus built and can be compared with the first concept.

Another possibility is to combine the previous system with the satellite power system. For example, the solar panel charges the battery. This means there is a strong current going from the panel to the battery. By using this current a magnetic field can be generated. In this case it is no longer required to have a minimum resistance, and hence, the efficiency can be increased enormously. Of course, there are also downsides to the approach, such as that the torquer and the power system are combined. This means that they cannot be developed separately. If this concept would be chosen in a future satellite that is one of the main challenges. This challenge cannot be replicated in the thesis however. Therefore this concept is only considered in theory.

The standard solution for a CubeSat magnetic torquer is a torquer with a ferromagnetic core. In this thesis it was not possible to build a torquer with a ferromagnetic core because the ferromagnetic material would make it much more difficult to build. One of the drawbacks of a ferromagnetic core is a increase in volume required for the torquers. The reason more volume is required is that a long and slender ferromagnetic core is better than a short and thick core. Therefore the torquers should be put on top of each other, allowing for maximum length.

Measuring the torquers can be done with magnetometers. It is important to build a reliable testing platform in order to fairly compare the different systems. The measurement system has to take many things into account. It is especially important to eliminate interference from the environment such as electrical equipment and to calibrate the sensors. Another thing that is very important is to locate the sensor and torquer very accurately.

The effect of the environment was eliminated by calibration. This only eliminates the static environment. As soon as something is moved the calibration is off. One of the main culprits was discovered to be the elevators of the building. The measurement was disturbed when the elevator was moving. The location of the torquer and sensors was done using a PCB. This eliminates most of the measurements because the components on a PCB are located quite accurately. In order to further improve the measurement, a test board was made with nine sensors. Combining the results from nine sensors increased the accuracy of the result. It was however clear that the variance in the measurement was quite large which means there is room for improvement in the measurements.

The test results show that the torquers designed and build for this thesis meet the requirements given for Delfi-PQ. Based on the test several recommendations can be made for the future. First it was found that the current switching converter is not good. Secondly it was found that the power efficiency of the torquers that were built were within requirements, but based on theory the other two concepts may improve power efficiency even more.

The systems are evaluated based on the volume they occupy, the mass the power they need to function, the maximum torque they can deliver and the ease by which they can be implemented. Also the ease of construction and ease of system integration is considered. For the magnetic moment it is possible to use the theoretical performance and the measured performance of all systems except the ferromagnetic system.

Based on the results choices can be made in the future, depending on required performance. It is conceivable that ease of implementation is sometimes more important than volume or a strong torque or the other way around. Based on the experiences when constructing the various systems. It can be recommended to

consider a PCB system for the next Delfi project.

This recommendation for the best system is given with the current satellite in mind but is intended for a follow up satellite. Based on the potential for improvement and the small volume, if the next Delfi satellite resembles Delfi-PQ it is best built with a magnetorquer based on coils embedded in the PCB's, depending of course on the mission requirements.

If much more torque is required it may be better to invest in ferromagnetic core magnetorquers. In order to demonstrate a further integrated technology and increase volume for the payload, while improving power efficiency it is a good idea to combine the PCB as used in this project together with the solar panels or other parts of the power system. That way the power usage can be lowered even more. By having coils in the internal layers of the satellite PCB's, volume can be saved and importantly construction is easier. The downside of this approach is that some of the modular approach to the satellite design is lost.

Furthermore it is recommended that all satellite systems that consume or generate electric current undergo magnetic testing. The test developed in this thesis cannot perform this task very accurately, but the hardware may already be good enough if some time is invested in the software and calculation method. This knowledge can then be incorporated in the design of the satellite attitude control. By doing this, the design may be adapted such that the net disturbance torque is minimized. This can further reduce the power needed for magnetic attitude control.

Contents

1
Introduction

For Earth Observation missions, propulsive manoeuvres, and high speed radio communication a stable and well controllable satellite platform is needed. Providing this in a small satellite is a real challenge. In order to provide stability a (external) control torque has to be generated. In low Earth orbit one of the best ways to generate this torque is through magnetic forces. This provides an external torque through interaction with the magnetic field of the Earth.

TU Delft will launch a satellite called Delfi-PQ. Delfi-PQ is a pico satellite, which is a small satellite of mass less than one kg. It is a PocketQube satellite by adhering to the PocketQube standard. In order to stabilize this satellite a magnetic control torque is required. To design the magnetorquer some requirements have to be met. The most important requirements are extremely low power consumption, and a minimum magnetic moment for each magnetorquer. Also ease of construction, and volume needs to be taken into account. To meet these requirements, a magnetorquer will be designed, built and tested.

Furthermore, an investigation of possible other magnetorquer concepts is done for the benefit of future PocketQube Satellites. The main research question will be: Which is the most advantageous magnetic attitude control system for reducing angular rates of a PocketQube?.

The research methodology is to do a case study into multiple concepts for PocketQube magnetorquers. By designing the torquers, building them, and testing them experience will be gained where the challenges are and how to overcome them.
During the thesis two magnetic torquers were built, in both cases a detailed concept design was made. In addition to these two torquers a test board was developed and produced, including software to operate it. One of the magnetic torquers will serve as a prototype for the flight model torquer of Delfi-PQ.

This thesis will start with a short description of Delfi-PQ and the further context of the research project in the first two chapters. In chapter three the research objectives and research questions are outlined. The fourth chapter will provide a short theoretical background to magnetic attitude control.

Chapters 5 through 8 will deal with the requirements on the magnetorquers, the magnetorquers will be modeled and designed. The testing of the magnetorquer will be described in chapter 9 through 11. After the testing a trade-off is presented between the concepts. This follows the methodology of the research where each concept is explored and then compared. The conclusions and recommendations form the final chapter of this report.

2
Research Question, Context and Objectives

Once a small satellite is separated from the launcher upper stage it often acquires a rotational rate as a result of the separation procedure. Small moments created by atmospheric drag, magnetic fields and solar winds can also cause the satellite to rotate. Over time these can add up to substantial rotational rates. Rapid rotations of the satellite can negatively affect communications and power generation. In order to manage the rotational rates of PocketQubes and Delfi-PQ in particular it is envisioned that a magnetic control system is employed which will reduce the rotational rate of the satellite.

Such a system typically consumes a lot of power and the power budget for the PocketQube is very small. Therefore, the external objective is to provide a low power attitude control system. An active system is required, in order to facilitate possible subsystems such as a propulsion module or a directional antenna.

This research project is intended to support Delfi-PQ a satellite being constructed by TU Delft. While it is exciting to work on a real project, the research objectives need to be sufficiently interesting from an academic perspective. The context of the project consists therefore of two entities, on the one hand DELFI-PQ which has a clear mission statement, and on the other the thesis project. In order to meet the academic level it is required to move beyond designing the subsystem, and also do research.

2.1. The Research Situation

The research project will support the Delfi space program of the TU Delft and in particular deliver a subsystem prototype for Delfi-PQ. The Delfi-PQ project will deviate from earlier satellite projects in the program, by being a PocketQube instead of a CubeSat and by having less project phases. There will be a core platform that will evolve over time. Advanced subsystems, such as for instance attitude determination and control, as well as payloads will be developed as separate projects using a standard interface specification.

Delfi-PQ project: ***Delfi-PQ is a pico satellite demonstrating a reliable core bus platform and at least one advanced subsystem or payload.*** [1]

Because the topic of the research is magnetic attitude control it can be part of both the bus and the advanced payload. In order to function the satellite has to be stabilized. This means that the rate of spin of the satellite must be limited.

Magnetic attitude control can also be advanced enough be flown as an advanced subsystem. If the system is considered an advanced subsystem it will be the "payload". It will be a technology demonstration. Either way the challenge will be to minimize electrical energy consumption as much as possible.

In order to demonstrate that a PocketQube is a viable platform, which is again smaller and thus cheaper than a CubeSat, the project is using a more iterative method than before. This is required because employing a large team with fixed phases is more difficult and expensive. This mindset can also be used for larger spacecraft, therefore the results can be used in larger spacecraft. For example if the bus of the PocketQube is sufficiently capable it can be used in a Cubesat leaving more room for payload. [1]

The research should answer the basic need of the mission but also explore the possibilities of building an advanced ADCS system using magnetic control. The research is practice oriented and the problem that needs to be solved has already been identified. The satellite needs an attitude control system to function. Furthermore the satellite needs a raison d'etre, and the demonstration of an advanced attitude control system or a science payload could fill that need.

The main challenge is that very little power and volume is available. Earlier systems for magnetic attitude control need more capability but have different operational circumstances and generally more available power. From that perspective it is important to reduce the energy required for the attitude control system as much as possible while scaling down the attitude control system.

Some preliminary research has already been done, !!! like what?!! the problem that needs to be solved is recognized. From the problem identification phase there are also some questions identified:

- What is the best way to build a magnetorquer for Delfi-PQ?
- How can be ensured that the system does not use too much power?
- What commercially of the shelf (COTS) components can be used?
- Can current solutions be scaled down to the smaller satellite size?
- Are CubeSat solutions still the best solution or is a better solution possible?

The challenge is to find a way to answer these questions in a scientific manner and at the same time use the knowledge gained to produce technology needed for the satellite.

2.2. Research Question

Based on a literature study performed ahead of this research there are many ways in which this objective can be met. For example, the actuators can be improved so that they consume less power. Alternatively, the sensors may be improved to reduce attitude errors. Improvement can be made to the control algorithms to reduce the required torque. Or the entire actuator architecture can be altered improving the efficiency of the system as a whole. The last option is chosen for this research project. This choice is made because this is one of the most interesting directions of study, one of the most promising options for improvement, and because it best aligns with the competencies of the researcher. Also scaling the satellite down means that the satellite gets different properties which means that different options may become less viable or more viable compared to a CubeSate magnetorquer. [2]

Therefore, the research question will be: Which is the most advantageous magnetic attitude control system for reducing angular rates of a PocketQube?

However, in order to meet the launch deadline of Delfi-PQ it is also decided to build, a system comparable to existing systems, but take care to build it as power efficient as possible.

In order to answer this question, the following sub questions have to be answered.

- What fundamentally different architectures can be used?
- How does the performance of each architecture compare to the others?
- How can the hardware be tested accurately?
- What is the most important trait of the system and what is the best way to balance the trade off between the architectures?

- How can the different systems be constructed?

How can the hardware be tested accurately is possibly the most involved sub-question. In order to answer the question, it is important to find out:

- How can the magnetic fields be measured?
- How can the torque generated be measured?
- How can the test be automated?
- How can be ensured that the test set up is impartial to the system?

Possible trade-off parameters for comparison

- Power consumption taking into account Capability
- Volume
- Cost of construction
- Time required for construction
- Mass

2.3. Methodology

The method of research is a case study comparison between different implementations of magnetorquers for PocketQubes. In order to find a suitable magnetic torquer for Delfi satellites a number of different options will be designed and compared.

The first goal of the thesis is to design the first version of the magnet torquers for Delfi-PQ which will also be used as a baseline for the future concepts. Because the launch of Delfi-PQ will occur in the near future, the design options for this system were limited. For the other designs there is a little bit more freedom.

The next goal of the thesis is to create and compare several different designs for magnetic attitude control torquers for PocketQubes. There are several key points where the systems can be compared. These are all particularly important to the Delfi program. Comparing the different designs will mostly be influenced by the electrical energy that is expended to attain a certain torque. In order to determine this the torque produced and the power required need to be determined.
This is first done theoretically. This theory is then also used to optimize the designs as much as possible. In addition to that, where feasible, the designs will be produced so that actual prototypes can be compared. There are two reasons for comparing prototypes rather than designs, first to confirm the performance of the design. Second because in production lessons may be learned that are not apparent as long as the designs stays theoretical. In order to compare the prototypes, a standardized test system will be developed.

This test is the third goal of the thesis and has to be design independent. In this case the premise of developing the testing independent from the design is used to be able to validate the test. Because the test is design-independent, the different designs can be compared in a fair manner. Moreover, if the test is design-independent, new designs can be compared to the previous system in the same way. It may be that next year another, possibly better, system is built. If the test system is still available the new system can be compared to the previous ones. In software design testing is often done automatically. The objective for this research project is to also automate the testing. If the testing can be done automatically less user bias is present. In addition the test system can be used to measure the magnetic fields of other subsystems.

Once the goals are achieved the research questions can be answered and recommendations for further research can be made.

3

Theoretical Background

The basic concepts of satellite attitude control are widely understood, however the way they are defined and used in this thesis work may differ from other sources. Therefore this chapter will provide a brief overview of the relevant concepts at a high level. Furthermore, in addition to the glossary, the relevant terms, and their origins are introduced here. In this chapter there is also a section going into more detail about torquer coils.

3.1. The Need for Satellite Attitude Control on Small Satellites

In low Earth orbit there are disturbance torques which act on a satellite. These torques will affect the rotation of the satellite. Disturbance torques may be caused by aerodynamic forces, radiation pressure, solar winds, and most importantly magnetic field interactions[3]. This will cause a satellite in Earth orbit to acquire a rotation around its own axis.

A satellite that rotates has several disadvantages. For example, antennas cannot be aimed at receivers. Also solar panels have less yield due to rapidly changing illumination. Especially satellites that need a lot of power require pointing their solar panel at the sun. This cannot be done if the satellite is rotating around its own axis uncontrollably. Therefore most satellites have a means to stabilize their attitude.

In addition to advantages for communication and power generation, if the satellite has an Earth observation payload or a propulsion system attitude control is required.

Restricting the tumbling rate is important for both reliable power generation and communications. Some design to restrict tumbling rates is included on about 80% of nanosatellites. About 40% of nanosatellites uses active (magnetic) control, 40% use passive magnetic materials, and 20% is free to tumble. This shows that attitude control is not absolutely necessary, but the majority of nanosatellites still choose to include it. [4]

As mentioned, unintended torques generated by magnetic forces cause the satellite to tumble. The opposite can also be achieved. By creating intentional magnetic forces, the attitude of the satellite can be controlled. Magnetic control is one of the most often used methods to control the attitude of nano satellites. It is also present on much larger satellites as long as they are in low Earth orbit, see for example figure 3.1 a photograph of the Hubble Space telescope. Further away from the Earth the magnetic field is weak and magnetic torques are also less.

3.2. Magnetic Satellite Attitude Control

By placing magnets on a satellite in low Earth orbit, that satellites attitude can be controlled with respect to the magnetic field of the Earth. This is either done by electromagnets, or permanent magnets, where the electromagnets have the advantage of being able to change the way they actuate during the mission. Permanent magnets have the advantage that no power is required to operate them, but have the drawback they cannot be turned off.

Also use is made of ferromagnetic materials, which become magnetic due to external magnetic fields, to

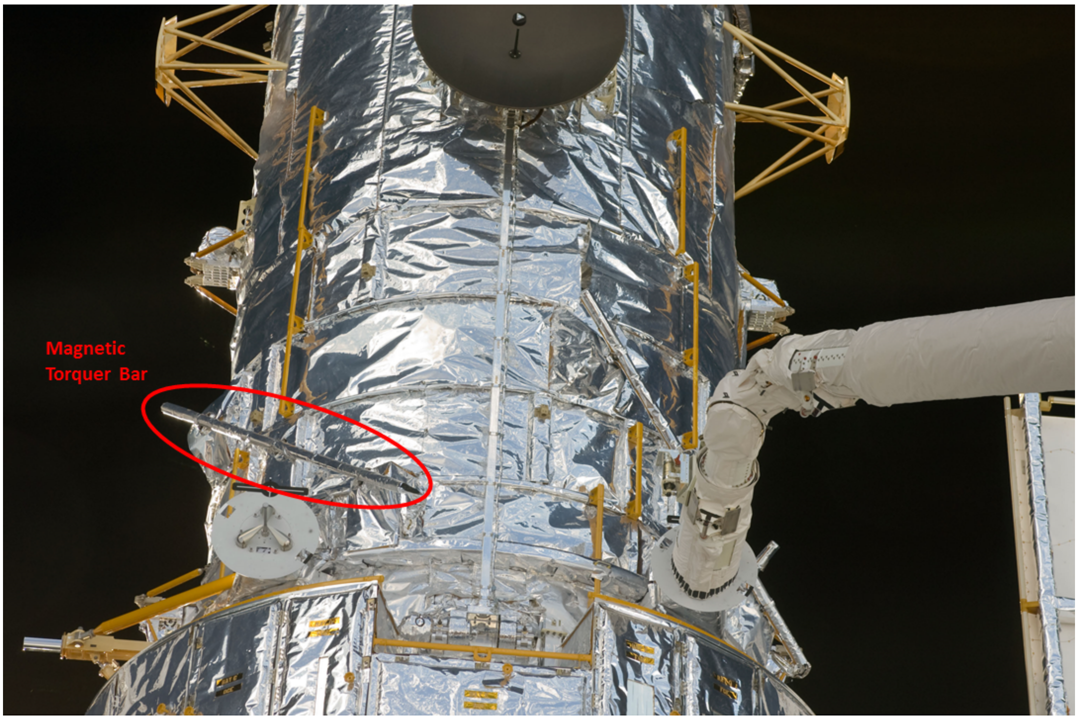

Figure 3.1: One of Hubble's magnetic torquer bars appears in this photograph taken during the final servicing mission to Hubble. Credits: NASA

enhance the performance of the magnetic control system. An electromagnet used to control the attitude of a satellite in orbit is called a magnetorquer. They are generally made of a copper coil and may have a core of ferromagnetic material. Because an electromagnet can be turned off and on, as well as change the direction it's magnetic field acts, this is used in active magnetic control.

Passive magnetic attitude control means that the system will not use any power, and that the system cannot be altered once in orbit. However the system can stabilize the satellite so that it can perform it's function, without using any power. This works by placing a permanent magnet on the satellite together with hysteresis rods. Hysteresis rods are magnetic dampeners, if they are rotated in a magnetic field they counteract this rotation and turn the rotational energy into heat. Hysteresis rods are strips or bars of ferromagnetic material. [5][6]

A reason to choose a passive system is that the power budget could be so constrained that an active system becomes too weak due to a lack of electrical power. A reason to choose an active system on the other hand is that it is more future proof, as it can be combined with mechanical control such as gimbals or reaction wheels. These mechanical control systems can point the satellite much more accurately but they will rely on the magnetic system for saturation prevention and more general pointing.

3.3. The Advantages of Active Magnetic Attitude Control

Active magnetic attitude control has one major advantage over all other means of achieving attitude control for a satellite. It is the only way to generate an external torque on the satellite without using expendables.

There are other methods for attitude control, but they either require propellant such as thrusters, cannot be controlled such as passive magnetic control and gravity gradient stabilization, or they will be come saturated by disturbance torques such as gimbals and reaction wheels.

In addition to that, active magnetic attitude control requires no moving components and is quite strong, especially in low Earth orbit. These advantages combined make active magnetic attitude control is an often used technology in low Earth orbit satellites.

3.4. Drawbacks of Active Magnetic Attitude Control

Although magnetic attitude control has several advantages compared to other attitude control systems, there are also several disadvantages.

- Active magnetic attitude control requires a relatively large current or long actuation times, both of which result in a significant power consumption.
- Active magnetic attitude control is generally relatively imprecise in pointing mode compared to other attitude control methods.
- Magnetic attitude control adds a significant additional mass to the satellite, although the same is true for other attitude control methods.
- Magnetic attitude control efficiency depends on the magnetic field strength, and is therefore not useful in high orbits.
- Active Magnetic attitude control authority depends on the magnetic field direction, meaning that it cannot at all time control all three axis.
- Active magnetic attitude control accuracy relies on knowledge of the instantaneous external magnetic field.
- Active pointing by magnetic attitude control accuracy relies on predictions of the external magnetic field in the future.
- Measuring the external magnetic field can be particularly difficult because the satellite generates its own magnetic field. This drawback combined with the previous three are largely responsible for the limited pointing capability.

Improving the magnetic attitude control system can be achieved by tackling one of these drawbacks. It is harder to improve on the advantages.

3.5. Definition of Delfi-PQ, PocketQube and CubeSat

Throughout this document is referred to a PocketQube, CubeSat, or Delfi-PQ. A CubeSat is a 'nano satellite' with dimensions 10 cm by 10 cm by 10 cm. A PocketQube is is a 'pico satellite' that has a basic volume of 50 x 50 x 50 mm.

PocketQubes are called pico satellites because of their mass. Large satellites are generally thought of as satellites with a mass exceeding 1000 kg. Micro satellites are satellites with a mass less than 100 kg, and nano satellites are satellites with a mass of less than 10 kg. Pico satellites are satellites with a mass less than 1 kg.

The CubeSat standard has a basic volume 8 times larger than a PocketQube basic volume. CubeSats are often used in a multiple of this volume for example 1.5U, 2U, 3U, or even 6U, 4U and 12U. see figure 3.2. 1.5 2 and 3 U CubeSats are built according to the CubeSat design specification [7]. For CubeSat's with a larger multiple, such as a 6U there is a slightly different standard. Because the CubeSat has become very popular there is a lot of research papers available concerning them.

Similar to a CubeSat, the size of a PocketQube can be a multiple of the basic volume. In that case the size is referred to as a 2p or 3p PocketQube. Delfi-PQ will be a 3p PocketQube which means it has a volume of 50x50x178 mm see appendix E for a drawing. The increase of the third dimension is because it incorporates volume between PocketQubes normally empty. A PocketQube will be built according to the PocketQube standard. [8]

One of the reasons the CubeSat is so popular is the low cost. Because of the small size the costs per satellite are low. Also the small mass means many satellites can share one launcher, which reduces the launch costs per satellite. One drawback of sharing a launcher is that if one of the co-passenger satellites is poorly constructed, all satellites on the launch may be damaged. This is mitigated by using standard CubeSat deployers. Any damage will be contained in a single deployer. Therefore a CubeSat has to follow the size requirements very precisely. External satellite dimensions cannot deviate from the standard, otherwise the satellite will not fit in the standard deployer. This deployer concept is also used for PocketQubes, but of course the deployer is smaller.

A second reason for the CubeSat popularity is that a CubeSat is usually able to use more current technology and have shorter development times. Larger satellites typically have a longer development and to reduce development risk often older components are used. CubeSats are lower cost projects and can generally take more risk. In addition to that, because of the small cost per satellite it is feasible to build multiple satellites. This allows certain subsystems can be produced in series if there is enough commonality between satellites. Also because of the standard size, systems can be reused for different satellites. [9]

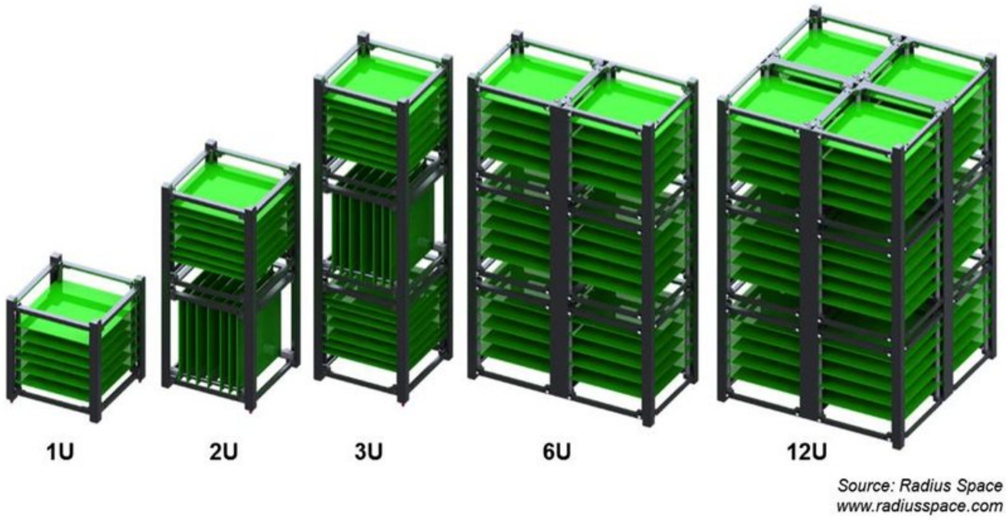

Figure 3.2: CubeSate frames, Radius Space

3.6. The Delfi-PQ Mission

The following is quoted from the Delfispace website. [1]
Delfi-PQ stands for Delfi PocketQube. Why a PocketQube? Delft University of Technology has entered the class of picosatellites to re-focus on space technology miniaturization. PocketQubes are an order of magnitude smaller than the well known CubeSat standard which formed the basis of previous Delfi satellite projects. Although a fixed international standard for the outer dimensions is lacking for PocketQubes, the building blocks are cubes of approximately 5 cm wide, so 8 times less volume compared to CubeSats. Where CubeSats have grown the past decade to a serious business with mature capabilities, PocketQubes and/or picosatellites are still in its infancy. Like in the early days of CubeSats, many people at this moment regard PocketQubes as merely educational toys rather than promising platforms.

3.7. Definition of Terms

Here some terms are defined that are used later on in the report.

Magnetic Flux Density

The magnetic flux density can be visualized by the density of the magnetic field lines in a certain area. This quantity is denoted in the unit Tesla, which will be abbreviated to T. This is the quantity that is measured by a magnetometer. In weaker magnetic fields the magnetic flux density is often denoted in milligauss, mG. The magnetic field measurements in this report are usually expressed in mG.

Magnetic Moment

The magnetic moment is used to calculate the torque generated by a magnetorquer. The magnetic moment is denote in Am^2 which is Ampere times area. In this report this quantity is often denoted as m and sometimes as μ

Dipole

A pair of equal and oppositely magnetized poles separated by a distance. In this thesis a dipole is typically the result of a magnetorquer, and is meant to mean a magnetic dipole.

Magnetic Permeability

Magnetic permeability is the constant in the proportionality between magnetic induction and magnetic field intensity. A substance with high magnetic permeability will amplify a magnetic field applied to it.

Magnetic Coercivity

A measure of the strength of the magnetic field that needs to be applied before the material changes its internal magnetic field.

Magnetostriction

Mechanical deformation of a ferro magnetic material due to an applied magnetic field.

Hard Iron

Hard iron is usually a ferro-magnetic material with a high coercivity. Hard iron is often synonymous with a permanent magnet. Hard Iron calibration aims to remove all permanent magnets in the vicinity from the measurement result. Hard Iron magnet torquer cores have a high residual magnetic dipole after the magnetorquer is switched of.

Soft Iron

Soft iron is usually a ferro-magnetic material with a low Coercivity. Soft iron is often synonymous with a temorary magnet. A soft Iron substance will produce a magnetic field due to the influence of other magnetic fields. Soft Iron magnet torquer cores have a very small residual magnetic dipole after the magnetorquer is switched of.

3.8. Magnetic Actuation by Magnetorquers

On satellites magnetorquers are used to generate an external moment to the satellite. The torque generated by a torquer on the satellite not only depends on the torquer but also the strength of the external magnetic fields. It is therefore typically only used in low Earth orbit because the magnetic field strength reduces with altitude. The torque generated by an electromagnet, or a magnet in general is given by eq 3.1, where τ is the torque, generated around the magnetic axis of the magnet, μ_{loop} is the magnetic torque of the electromagnet, and B_{ext} is the external magnetic field. Because the torque is generated around the magnetic axis of the magnet it is useful to have the magnetic axis coincide with the inertia axis is of the satellite, this simplifies the control and generally reduces the required torque.

The magnetic torque of a current loop is given by eq: 3.2. Where I is the current that runs through the loop and A is the area inside the loop.
A magnetorquer can be fitted with a core. If no core is fitted, this is usually called air core. The core material needs to have special magnetic properties. When properly applied this can lead to massively improved performance versus power. A magnetorquer without a ferromagnetic core is called an air core even if there is a material that forms the center of the coil, such as a polymer. The magnetic properties of the material determine if it is a 'core' or not.

3.8.1. Magnetic Control Equation

When a magnet is placed in an external magnetic field a torque is created unless the magnet's magnetic field lines up with the field lines of the external magnetic field. This can be expressed as equation 3.3 [10].

In this equation τ_c^B is the torque on the satellite as a result of the coils in a satellite body frame. The vector m_c^B denotes the magnetic moment of the coils in the same frame and b_E^B is the local Earth magnetic field vector.

$$\tau = \mu_{loop} \times B_{ext} \tag{3.1}$$

$$\bar{\mu}_{loop} = I \cdot A \tag{3.2}$$

$$\tau_c^B = m_c^B \times b_E^B \tag{3.3}$$

3.9. Torquer Core Materials

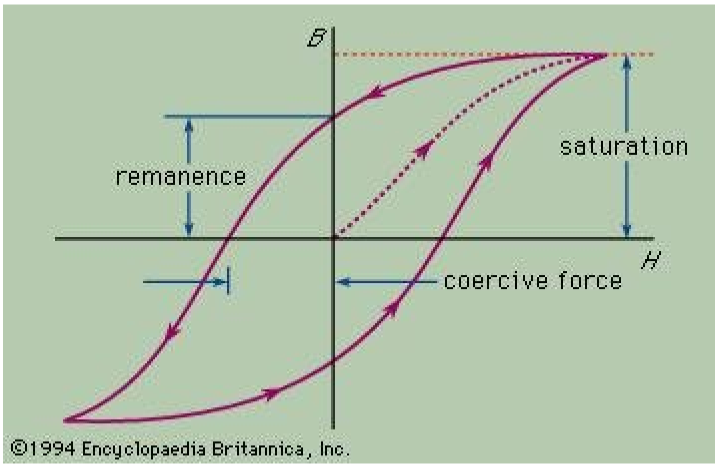

Figure 3.3: hysteresis https://www.britannica.com/science/hysteresis

Adding a core material changes equation 3.2 to 3.4. The variable μ_r is the relative magnetic permeability. This is relative to the magnetic permeability for a vacuum, but for air it is approximately equal to one. Compare the values given for μ in table 3.4 with the value in eq 3.2. The influence of the relative permeability can increase the magnetic moment extremely.

However, equation 3.4 is valid for infinitely long narrow coils. For short truncated coils the relation is much more complicated, and, less advantageous. The formula for shorter thicker cores is given in section 4.6.

$$\bar{\mu}_{loop} = \mu_r \cdot I \cdot A \tag{3.4}$$

Typically a structure is required to replace the core if an air core is used anyway to ensure stiffness of the torquer, however there generally is still a mass penalty associated with using a core, because the structure in an air core can be lighter.

The optimal material properties for a torquer core are not clearly defined in literature. It is important to have low coercivity, leading to low hysteresis losses, and it is also necessary to have high relative permeability. However low coercivity generally comes with a low saturation point. Typically a high magnetic saturation point would be more optimal because it can increase the strength of the torquer. It is also good to have low magnetostricion, which is the coupling between the magnetic field of the material and the shape of the material.

Mu-Metal can have a relative permeability of 100,000, and it could be possible to go even one magnitude beyond that. This means the solid core should outperform. However, relative permeability is only linear in a very narrow range. It does not mean the magnetic moment is multiplied by the core indefinitely. Depending on the saturation level of the core material, the core will have a maximum. After that the core will not amplify the torquer any more. See figure 3.4 for a list of material properties. Another drawback could be the influence of external magnetic fields which means the core could be saturated more easily, as well as get magnetized unexpectedly.

Table 12.5 Selected magnetic properties of different soft magnetic materials

	Composition	Relative permeability μ_i	μ_{max}	Coercivity H_c (A m^{-1})	Saturation induction B_s (T)
Iron	100% Fe	150	5000	80	2.15
Silicon–iron (nonoriented)	96% Fe 4% Si	500	7000	40	1.97
Silicon–iron (grain-oriented)	97% Fe 3% Si	1500	40 000	8	2.0
78 Permalloy	78% Ni 22% Fe	8000	100 000	4	1.08
Hipernik	50% Ni 50% Fe	4000	70 000	4	1.60
Supermalloy	79% Ni 16% Fe, 5% Mo	100 000	1 000 000	0.16	0.79
Mumetal	77% Ni, 16% Fe 5% Cu, 2% Cr	20 000	100 000	4	0.65
Permendur	50% Fe 50% Co	800	5000	160	2.45
Hipereo	64% Fe 35% Co, 0.5% Cr	650	10 000	80	2.42
Supermendur	49% Fe 49% Co, 2% V		60 000	16	2.40

Figure 3.4: table from reference [11]

A magnetorquer with a magnetic core will have a maximum magnetic moment determined by either the magnetic saturation point or the hysteresis behavior of the material. A generalized hysteresis curve can be seen in figure 3.3. In the figure, the magnetic field created by a coil is denoted with H. Variable B is the magnetic flux density. As can be seen there is a maximum that is determined by the saturation of the material.

When the material is not magnetized and a magnetic field H is applied the dotted curve is followed. This will take a finite amount of time. A magnetic field cannot be applied instantaneously because of induction in the coil that generates H. Once the magnetic field density reaches a certain value it will not return to zero when H is reduced to zero. If H remains small enough hysteresis will not occur, and B will return to zero if H returns to zero.

For most control methods it is necessary that hysteresis does not occur in a magnetorquer. This limits the

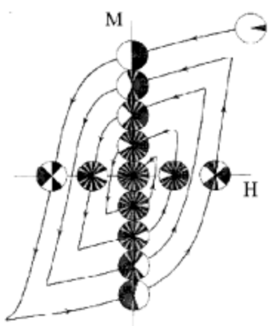

Figure 3.5: Reducing core field back to zero, the circles describe the domain orientation in the material. [12]

maximum torque by the magnetorquer. The reason is that otherwise the controller does not know precisely the value of B, as it can only control the value H. The point where hysteresis will occur is material specific.

This hysteresis behaviour is created by crystals in the material that change their orientation to align with the magnetic field. This also means that traveling through the complete hysteresis loop takes up energy. This can be used to reduce rotational rates of satellites as well. [13]

Another drawback of a core material is that often a residual magnetic field remains. This is especially true if the core is driven to saturation. In using the core it is very important to stay within the linear response region of the material, otherwise the remaining field will be strong.

It is possible to use the hysteresis principle to generate a continuous torque without using power, if the remnant magnetic field is strong enough. i.e. using a higher coercivity. This however may require a determination of the remnant magnetic field of the core in flight, which is difficult. It also complicates the control laws, since the magnetic field cannot be switched quickly. Not only that, switching also takes a lot of energy because demagnetizing the core will require several loops trough the hysteresis loop.

An estimation of this effect is given in literature, where it is concluded that if for an idealized hard iron core, the magnetorquer is much more efficient for a case where the magnetorquer has to switch on or off or reverse polarity only a few times per orbit[14]. However a soft core magnetorquer is more efficient if the torque has to change every few seconds. A hard iron core would have more coercivity and more hysteresis, whereas a soft iron core would have little to no hysteresis and typically negligible coercivity.

Once the core has become magnetized it is possible to bring it back to zero by applying an alternating current to the coil and steadily decrease the current level. This way the core follows the path as in figure 3.5. The result is that the magnetization value of the core is reduced to near zero.

3.10. Coil Area Relation

While it seems that an air core torquer is inefficient compared to a ferromagnetic core, since this multiplies the effect so strongly, this does not have to be the case. An air core torquer is magnetically more clean if there is no current in the torquer, which reduces unpredictable torques remaining after switching off the torquer. In general a small magnetic field will remain in the ferromagnetic core after there is no more current in the loop. This is smaller if coercivity is smaller. This remaining field will act as a disturbance torque which means the control system is active more often.

More importantly there is another way to increase the efficiency of a torquer when no ferromagnetic core is used. The magnetic field generated by the torquer is given as equation 3.4, where $\bar{\mu}_{loop}$ is the strength of the generated magnetic moment. Instead of using a ferromagnetic core the area could also be increased. One application of this concept would be a flat square spiral on the back of the solar panel, or a trace on a PCB[15].

Comparing to the flat spiral the ferromagnetic core torquer, the latter outperforms from a relative magnetic permeability of the core of about 25. This is for an equal amount of copper wire. The spiral has an enclosed area thousands of times larger than the core torquer. The reason the solid core torquer outperforms is that the magnetic moment also scales with the number of winding. Reducing the area of the coil increases the number of winding that are possible with the same wire.

It could be argued that the flat spiral would need less mass, and could thus take more copper, however, the bonding of the wire will bring in additional mass, or in the case of a PCB and extra layer of copper would be added which also increases mass.

3.11. Relation between Magnetic Dipole and Magnetic Moment

Magnetometers do not measure the magnetic moment of the torquer, instead they measure the magnetic field, more specifically the local magnetic field density. This measured in milligauss or microTesla. This measurement is related to the magnetic moment as in formula 3.5. The equation relates to the magnetic field

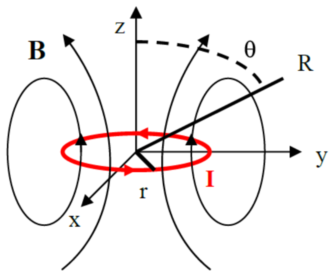

Figure 3.6: Sketch of magnetic field created by current loop. [16]

as in figure 3.6

$$\mathbf{B_r} = \nabla \times \mathbf{A} = \frac{\mu_0}{4\pi}\left(\frac{3\mathbf{r}\left(\mu_{\mathbf{loop}} \cdot \mathbf{r}\right)}{|r|^5} - \frac{\mu_{\mathbf{loop}}}{|r|^3}\right) \tag{3.5}$$

By placing the magnetometers in locations where the inner product between μ_{loop} and $\mathbf{r}$ is zero makes it easier to evaluate the formula. This is the same as when the angle θ in figure 3.6 is ninety degrees. This is important for validation when using this concept to measure the magnetic moment.

3.12. Coil Control Parameter

For an active magnetic control system with three orthogonal coils the vector m_c^B can be expressed as in equation 3.6. The component N_i is completely determined by the design of the magnetorquer. The current I_i can depend on several things like battery voltage, temperature of the coil the power supply in general. It is therefore required to measure the current when the coil is activated.

If the design can be very tightly controlled it is possible to accurately calculate the parameter N_i. This does require that the magnetorquer is built exactly as modelled, or that the model is adapted to what is built. This calculation does become more difficult for non-circular coils or coils with a ferromagnetic core. Another option to determine N_i is by testing.

$$m_c^B = \begin{bmatrix} N_x \cdot I_x \\ N_y \cdot I_y \\ N_z \cdot I_z \end{bmatrix} \tag{3.6}$$

As said, N_i is determined before flight. The better this vector is known the better the controller will perform. The controller can only control I_i, b_E^B has to be measured. Measuring this vector can be quite difficult because of the internal magnetic field of the satellite.

3.13. Control Algorithms for Magnetic Attitude Control

The study is focused on hardware rather than control theory. Control theory is a very interesting field, especially in the magnetic domain, because the actuator capabilities change depending on orbit location. Which means that the control algorithm has to be predictive to achieve optimum results. [17] However the basic system of the sensors and actuators can be designed without predictive control.

If necessary the B-dot algorithm is used on this project. This controller is designed to reduce rotational rates to zero. [18] This has also been used on previous Delfi projects [19]. This algorithm is not predictive, and it thus it cannot point the satellite in a certain direction, but instead it reduces the angular rate. Hence only the current ambient magnetic field has to be known. If pointing is needed the ambient magnetic field needs to be predicted because future torque generation capability depends on the ambient magnetic field, which is beyond the scope of this thesis.

4

Requirements and Design Options

In order to point and de-tumble the PocketQube satellite Delfi-PQ, magnetorquers are used. To ensure rapid development requirements were set for the design from top down to reduce complexity and allow development of other subsystems simultaneously. The starting requirements are given below.

- Three magnetorquers shall be placed in orthogonal configuration (X, Y & Z).
- The magnetorquers shall not contain a magnetic permeable core.
- The magnetorquers shall be driven by +3.3V, -3.3V and 0 V only.
- The magnetorquers shall generate at least 0.004 Am2 at 3.3V.
- The maximum current shall be equal or less than 50 mA at 3.3.V, which yields a minimum steady-state resistance of 66 Ohm.
- The height (out-of-plane of the PCB) of each magnetorquer shall be equal or less than 11 mm.
- The total set of three magnetorquers shall be placed on less than half of the available printed circuit board area of the PQ9 board, taking the keep area for spacers and PQ9 connector into account.
- Each magnetorquer shall have at least two structural attachment points to the PCB, for which the selected bolt will go perpendicular through the PCB.
- Each magnetorquer will have a to-be-specified electrical connection to the PCB.
- The system is active, and hence can be switched on and off.

It is thought by the satellite designers that power consumption will be the most important constraint on the usage of the system. It therefore needs to be optimized with respect to power usage, while staying inside the allotted volume. It is assumed that the volume constrains will automatically ensure that any mass constraint is met. Therefore no mass requirement was set for this subsystem.

4.1. Requirements

The requirements outlined in the previous section are very limiting in the design options. This is thought necessary for the quick development of the torquers for Delfi-PQ. However some of the requirements have to be renegotiated because they were considered unfeasible after starting the design.

Because the requirement for the torque is clearly stated at 0.004 Am2 this is the design goal for all magnetorquers. Also the volume requirement makes the design space clear. While the performance of the system can be increased by increasing the volume, the satellite volume is limited and increasing the volume of the torquers will decrease the volume available for other subsystems.

The maximum current requirement was rewritten as a maximum power requirement during the course of the design phase. A larger current can easily be supplied by the satellite, however power is the real problem. As the bus voltage is fixed the power is determined by the current, however it turned out that the system was not feasible at 3.3 V. Therefore it was decided to eliminate the requirement that the magnetorquer may only be driven by +3.3V, -3.3V or 0 V. The reason is that a magnetorquer generates a magnetic moment that is given by $m = n \cdot I[Am^2]$. The factor n is determined by the torquer and I is the current put in the torquer. If the torquer can only be powered by 3.3V, the electrical resistance is fixed. With the given current and voltage the resistance is 66 Ω. Quite early in the design phase it was recognized that this resistance is too high to make the torquer power efficient. Copper wire cannot be found thin enough to increase the electrical resistance to 66 Ω. The amount of wire would be so large that there would be an issue with the volume. Because power increases with the square of the voltage and decreases linearly with resistance, it is more power efficient to have low voltage, low resistance.

Furthermore, even though magnetic permeable core materials were excluded, they can give substantial benefits and should be examined. This goes for several other requirements too. These requirements apply to the prototype for Delfi-PQ but do not apply to all the designs. Having these requirements makes it much easier to start the design phase.

It was therefore decided that the torquer system would be allowed to modify the voltage, and the maximum power would still be 165 mW. But the torquer design has the freedom to select the voltage and current. The main reason for this is to make sure the system is power optimal. The principle design driver is the energy efficiency of the system, and the design objective to generate as much magnetic moment for as little as possible electrical energy spent.

4.2. Design Options

Based on the requirements several design options are considered. For all systems considered, it is required to produce coils that generate a magnetic moment. The first option determines how the coil is built. Two options are available, first wind thin wire around a spool to create a coil. The second option is to 'print' a coil on a printed circuit board.

The second design option is related to the voltage across the coil. Two ideas were possible. First was a novel idea to place the coil between for example the solar panel and the battery. Whenever the solar panel is charging the battery, there is a current flowing from the solar panel to the battery. Normally the voltage drop is kept as low as possible. Therefore it is possible to have a low voltage over the coil and a large current. There is a large drawback here too. The current flows only one way so there has to be a switch in the solar panel that can control the direction. Also there has to be a bypass line for when no magnetic field is required. A system that is built in this manner will be called a *secondary current utilization* in this document.

Another way to reduce the voltage over the coil is by a voltage divider or resistor. The drawback is however that this does little to improve efficiency because the efficiency gained in the coil is lost in the resistor. However there is a way to reduce the voltage of a DC current efficiently by using a switching converter.
The next design choice is the conductor material. It was decided to use copper early on in the design process. Copper is the best conductor in terms of volume, and volume is one of the main limiting factors. Having a low electrical resistance means that the coil can be very large for a low resistance. This should increase performance. Based on these choices four possible systems are envisioned. Each has a set of different characteristics.

- A torquer made out of copper wire, without a ferromagnetic core, thus an air core magnetorquer
- A torquer made out of coils printed on a PCB, also an air core, which will be referred to as a PCB coil.
- A torquer made out of copper wire, with a ferromagnetic core, thus a ferro-core magnetorquer
- And a coil that is a secondary utilization of an existing current, which is also made using a PCB.

4.3. Voltage

In particular, since power depends on the resistance as $W = R * I^2$ (W is power, R is resistance) and the torque is given by $n \cdot I$ the goal is to maximize n while reducing $R \cdot I$, see 4.2. However the multiplication of the resistance with the current gives the voltage see equation 4.1. Reducing the voltage thus increases efficiency of the system.

$$V = R \cdot I \tag{4.1}$$

$$\eta = \frac{n \cdot I}{R \cdot I^2} = \frac{n}{R \cdot I} = \frac{n}{V} \tag{4.2}$$

The best way to reduce a DC voltage is using a switching converter. Switching converters or buck converters work by switching the current on and off. A buck converter only lowers the voltage, a boost converter only increases the voltage and a buck/boost converter can do both. A buck converter works by storing part of current flowing when the switch is closed in an inductor and a capacitor. Once the switch is open the current flows from the inductor and capacitor through the coil. When the switch is closed again the capacitor and inductor are charged again. Through this process the voltage can be reduced. Reducing the voltage is important for *each* concept.

4.4. Air Core

This magnetorquer is created from winding wire around a spool. From equation 4.3 it can be seen that it is advantageous to have a large area A and a large number of loops, N in order to get a large magnetic moment. Increasing the current will also increase the magnetic moment but increasing the current will also increase power usage. In order to optimize for power usage therefore, this N and A have to be converted into electrical resistance. That way the power efficiency can be found. The main challenge is fitting as much loops as possible in a small volume.

$$\mu_{coil} = N_{loops} \cdot I \cdot A \tag{4.3}$$

It was decided to build this concept. A description of the design and construction effort can be found in chapter 5. The primary reason to build this concept is that this is the concept that matches the requirements of Delfi-PQ.

4.5. PCB Coil

One of the easiest ways create a circuit of copper is the use of PCB production facilities. PCB's, printed circuit boards, are produced in batches by specialized suppliers. They are able to produce almost any shape and depth of PCB. In development of Delfi-PQ this manner of construction is used extensively. This type of magnetorquer is sometimes called a embedded magnetorquer or embedded coil. The PCB coil is further explored in chapter 6.

One of the drawbacks is that it can be used to create planar coils only. However PCB's can be stacked together to create multilayer PCB's which means a number of planar coils can be stacked upon each other to increase the number of loops. It is interesting to find out if this produces magnetorquers good enough for PocketQubes. This way of creating magnetorquers does not seem to be common in CubeSat's where mostly wire wound coils are used, but a number of examples can be found. For example this paper describes a system with a coil inside a PCB [15]. And there is a solar panel with integrated torquer coil called nano power P110. [20]

It was decided to build this concept of a PCB with an embedded coil. One of the reasons this concept was chosen to be built is that because a PocketQube is smaller, there is less volume available, and the torque required is less. Because on a PCB it is impossible to create as many turns as for a solenoid it is likely that the maximum magnetic moment is also lower. However there is a chance to make the magnetorquer more efficient by using a relatively larger area. As can be seen from table 4.1 the area of the surfaces in the satellite decreases less than the volume and the magnetic moment needed.
Putting a magnetic torquer inside the payload section of the satellite will reduce the volume available for other payloads. Putting an extra layer on a PCB is very thin and will result in imperceptibly small reduction

	CubeSat	PocketQube	factor
Side	L	$\frac{1}{2}L$	0.5
Area	L^2	$\frac{1}{4}L^2$	0.25
Volume	L^3	$\frac{1}{8}L^3$	0.125
Mass	DL^3	$\frac{D}{8}L^3$	0.125
Solar Power	ηL^2	$\frac{\eta}{4}L^2$	0.25
Inertia	$\frac{DL^5}{6}$	$\frac{DL^5}{64}$	0.167
Magnetic Moment	$\frac{6k}{DL^3}$	$\frac{2k}{3DL^3}$	0.111

Table 4.1: Comparison between CubeSat and PocketQube [2]

in volume available. Adding two extra layers of copper to a PCB will typically result in the same substrate thickness but will add the thickness of the copper which is typically about 100 μm.

4.6. Ferromagnetic Core

In order to investigate the ferromagnetic core magnetorquer it will be necessary to alter the requirements again, this time the required torque and the height of the system. The ferromagnetic coils will increase the strength of the magnets. But to make them efficient the shape has to be different.

From theory it is known that a long thin ferromagnetic core outperforms a short thick one of the same power[21]. The system that will be designed will try to take advantage of that fact. For this system there is an example which can be seen in figure 4.1 but with one important difference. What can be seen in the image is that the relatively long and thin torquers are both on the same side of the PCB.

Torquers for a nanosatellite are placed in different ways. The current way is shown in this CubeSat board in figure 4.1. In this example, the area inside the air core, on the underside of the PCB has been increased as much as possible and the length of the torquer rods has been increased as much as possible.
What should be done for a PocketQube is placing one long thin magnetorquer on one side of the PCB, and

Figure 4.1: CubeSat magnetorquer board with flight heritage see; https://www.cubesatshop.com/product/isis-magnetorquer-board retrieved(Nov 2018)

the other on the other side. This way they do not interfere with one another and it is thus possible to have longer, thinner torquers. In order to create a feasible system it may be required to increase the height above the PCB that is used by the torquers. The third torquer can then be either a PCB coil or a wire structure wound around both torquers.

This is not the only way to achieve a three axis system. For their ADCS Alba orbital have chosen three similar torquers with a ferromagnetic core. See figure 4.2 Both pictures do not show the inside of the torquer so it is unclear what the core dimensions are. The Alba orbital system takes a radically different approach than the one used in the CubeSatshop example. Alba Orbital have chosen to integrate as many systems as possible. The CubeSat example is a module, containing not only the torquers but also the relevant PCB with electronics and processing and software. The picture of the Alba System only shows all ADCS actuators. The the actuators are controlled from a different part of the satellite. Instead of having one PCB per subsystem,

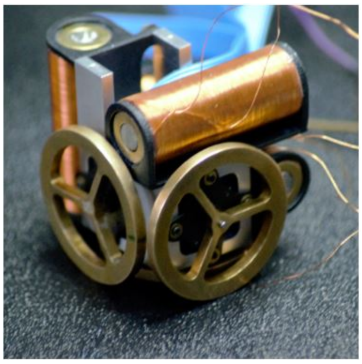

Figure 4.2: Alba Orbital torquers, including reaction wheels [22]

all systems are controlled from a single more complex PCB. This system is built for the Alba Orbital satellite platform called Unicorn-2.

One of our key insights from Unicorn-1 is that pico-satellites should be integrated instead of modular. There are 7 billion smart phones globally and all manufacturers have chosen integration as a design philosophy. Unicorn's key subsystems, EPS, OBC and ADCS are all integrated into one PCB. This allows the majority of the inside volume of the satellite to be used for the valuable thing.. payload! **Alba Orbital website**[22]

Because the Delfi program uses a modular approach the Unicorn method is not as feasible. If the design changes to incorporate a similar reaction wheel it may be integrated, but more likely the system should remain modular because each system typically linked to a (group of) student(s), which may not be able to move at the same speed.

It was decided not to build this system. The theoretical result is of course less reliable than the result of the other systems. The most important reason not to build this core is material. There are ferromagnetic magnetorquers used on many satellites. However the ferromagnetic material is not easy or cheaply come by. By using a inferior material the comparison would not be fair either. Additionally, time constrains forced the reduction of scope of the research work.

Another issue with the ferromagnetic material is that it can easily lose its properties if not handled properly due to thermal restrictions. There is a limited number of companies in the world that provide this service. The right material can multiply the efficiency of a magnetorquer, but it does come at a cost. The cost is both from reducing design freedom and actual cost. Because the suppliers of these ferromagnetic cores produce typically only standard sizes, requesting a new size of core will significantly impact lead time. Lead time for the standard size cores is already quite long. All this also increases the price. It is really only feasible if a large number of satellites would be built with the same magnetorquer. And, by using more integrated concepts such as the PCB coils it may be possible to achieve sufficient results without it.

4.6.1. CubeSat Magnetorquer

In order to design a torquer with a ferromagnetic core there is sufficient theoretical information available[23]. During the thesis much more attention is paid to the concepts that are built and no separate design for a torquer with a ferromagnetic core was made.

However in order to estimate performance of a torquer this state of the art CubeSat torquer is examined, see figure 4.3 and re-sized to fit in a PocketQube. The performance of this magnetorquer rod is, as can be seen very good. The torque generated is fifty times as high as the requirement for Delfi-PQ. The power required is only 125 % of the requirement. The device would never fit into the satellite however, in order to fit the length of the torquer rod would has to be cut in half. Doing this in practice is a bad idea because machining will affect the magnetic properties of the core. In theory it is a valid approach. For a torquer with a ferromagnetic core the ratio of $\frac{L}{r}$ where L is the length of the coil and r the radius, power required decreases with increasing $\frac{L}{r}$. This is contrary to an air core magnetorquer where efficiency efficiency typically increases

	NCTR-M002
FUNCTIONAL CHARACTERISTICS	
Magnetic moment	0.2 Am^2
Linearity (across operating range)	<± 5%
Residual moment	<0.005 Am^2
PHYSICAL CHARACTERISTICS	
Dimensions (l x w x h)	70 mm x 15 mm x 13 mm
Mounting feet	2
Mass	<30 g
Power	<200 mW from 5 V supply
ENVIRONMENTAL CHARACTERISTICS	
Thermal (operational)	-20 ˚C to +60 ˚C
Vibration (qualification)	14 g_{RMS} (random)
Radiation (TID)	n.a.
INTERFACES	
Power supply	5 V_{DC}
Data	n.a.
Connector	PCB pads
Mechanical	4 x M2 Socket Head Cap Screws

Figure 4.3: NewSpace CubeSat torquer with a ferromagnetic core [24]

when $\frac{L}{r}$ is decreased resulting in a large internal area.

For a solenoid, the magnetic moment is given by eq 4.4 where N_d is given by equation 4.5[25]. From this the power curve is then as displayed in figure 4.4, and the corresponding magnetic moment is shown in figure 4.5.

$$\mu_{coil} = NI\pi r^2 + \frac{\pi r^2 N\left(\mu_r - 1\right) I}{\left(1 - N_d + \mu_r N_d\right)} \tag{4.4}$$

$$N_d = \frac{4\left[\ln\left(\frac{l}{r}\right) - 1\right]}{\left(\frac{l}{r}\right)^2 - 4\ln\left(\frac{l}{r}\right)} \tag{4.5}$$

Because the ratio of length versus radius is so important it is assumed it can be kept constant in this case. This may not be a valid assumption depending on the difficulty of producing/obtaining the material. It may be necessary to accept a different thickness.

$$\mu_{coil} = NI\pi r^2 \left(1 + \frac{\left(\mu_r - 1\right)}{\left(1 - N_d + \mu_r N_d\right)}\right) \tag{4.6}$$

If $\frac{L}{r}$ is kept constant and the material parameter remains constant, and equation 4.4 is rewritten as equation 4.6, it is clear that the magnetic moment is divided by eight, assuming the current is kept constant. This is because N is halved and r is halved and r is squared. The current may be kept constant but the electrical resistance of the coil is reduced because the number of coils is divided by two and the diameter of the coil is also divided by two. Therefore the resistance of the coil is divided by four. Keeping the current constant would mean that the voltage has to be reduced or the thickness of the wire needs to be reduced.

If $\frac{L}{r}$ goes to infinity, N_d goes to zero, and thus equation 4.6 reduces to equation 3.4, as $\pi r^2 = A$. This shows that equation 3.4 is only valid for long and narrow cores.

In this analysis the assumption will be made that the measures to reduce voltage or the usage of thinner

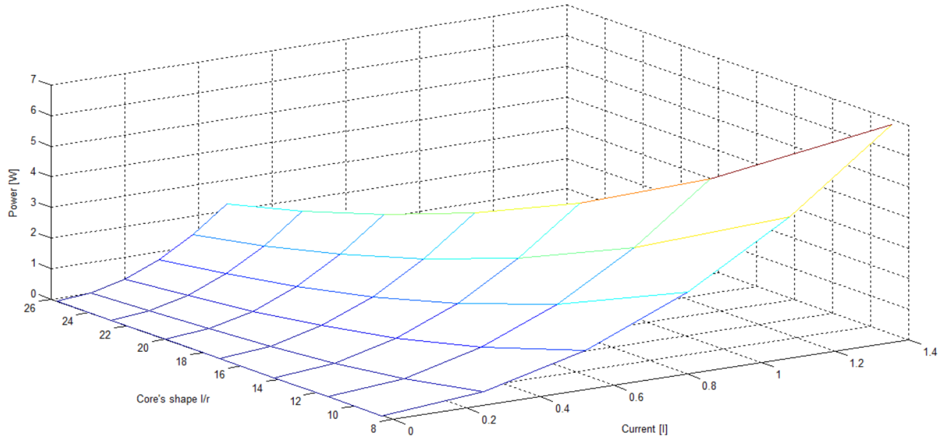

Figure 4.4: Power versus ratio length/radius for a torquer with ferromagnetic core [23]

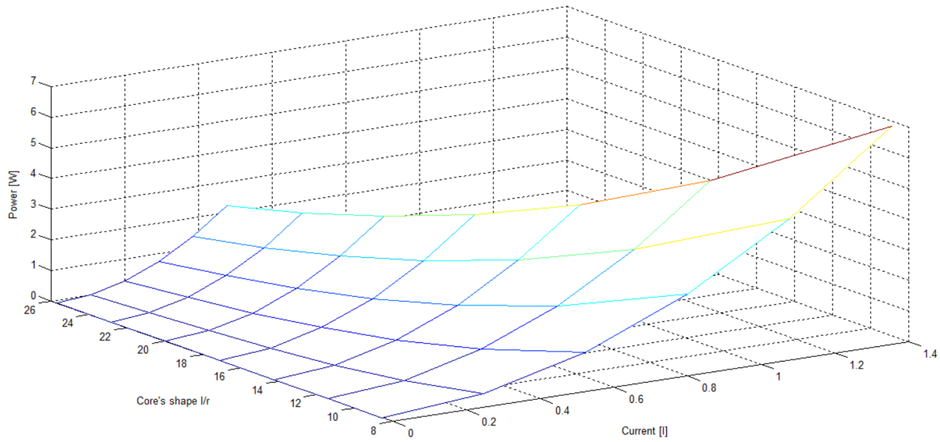

Figure 4.5: Magnetic moment versus ratio length/radius for a torquer with ferromagnetic core [23]

wire of mean the effective resistance of the torquer will not be a quarter of the CubeSat model but half of the CubeSat model. That means that the power, which scales linearly with the resistance is also half. With all these assumptions the characteristics of the torquer will be as in table 4.2.

	CubeSat(NCTR-M002)	PocketQube	
magnetic moment	0.2	0.025	$[Am^2]$
linearity	5%	5%	
length	70	35	$[mm]$
width	15	9	$[mm]$
height	13	7	$[mm]$
mass	30	5	g
Power	200	100	mW
Voltage	5	2.5	V

Table 4.2: Comparison between ferromagnetic torquer for CubeSat and ferromagnetic torquer for PocketQube

4.7. Secondary Current Utilization

This concept takes existing currents in a satellite and guides it through a coil, generating a magnetic field while using an extremely low voltage.

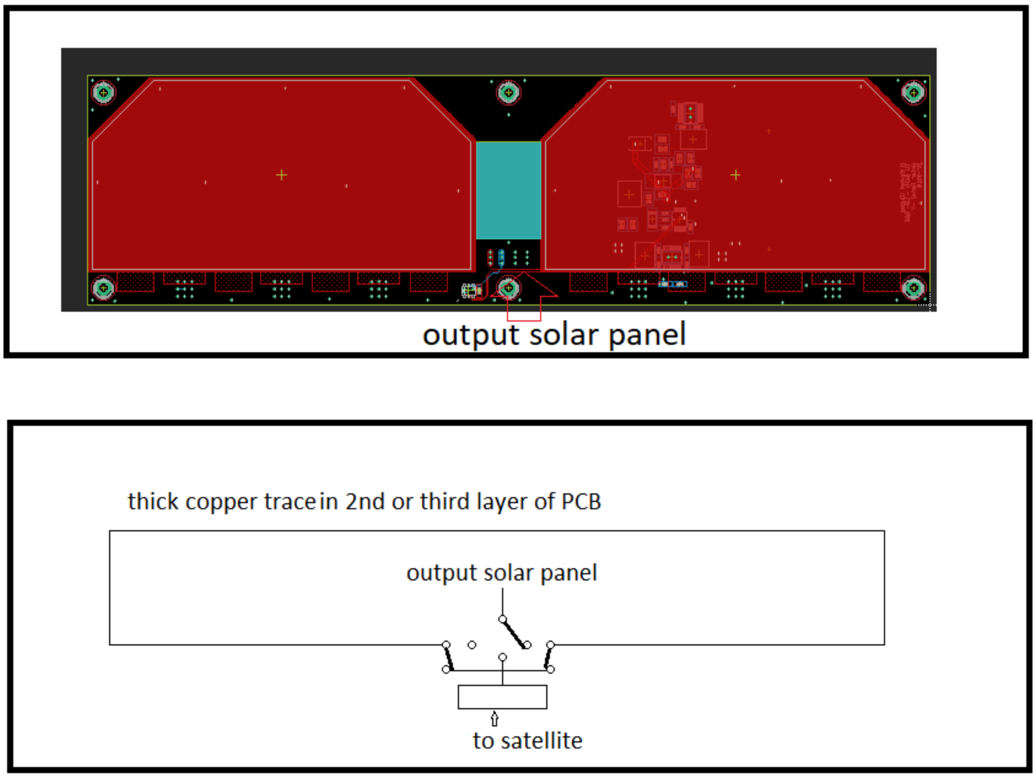

Figure 4.6: schematic drawing of a PocketQube solar panel

The two big question about this concept is where the coils will be placed, and what voltage drop will be allowed. The natural place for the x and y actuators is behind the solar panels. A drawback would be the high temperature of the solar panel, and the increased risk of failure of the power system.

The location for the z-axis coil this is not so clear. It could be placed in a separate PCB which also holds the ADCS controller. It was chosen not to investigate this concept for this thesis. However it is hoped that the experience with the PCB coil will help the development of this concept. A schematic of this concept is in figure 4.6. The top image is a schematic representation of the solar panel of Delfi-PQ. The output of the solar panel is indicated. The current can be utilized to generate a magnetic moment if it is led through the coil as depicted in the second picture. To this end a switch has to be added with the shown functionality.

Because the voltage drop can be much lower compared to a switching converter it is a very interesting concept to try. It does require integration into the EPS, which makes it less suitable for this thesis project. For this reason and an increased focus on testing the PCB and wire coils, this concept was not explored further.

5 Air Core Magnetorquer

This chapter describes the design and construction of an air core magnetorquer. This magnetorquer will form a prototype for the magnetorquer that should come on Delfi-PQ. The magnetorquer is designed to the requirements given in chapter 4.

The magnetic torque of a current loop is given by equation 5.1. Where the orientation is as in figure 5.1 For a coil without a magnetic permeable core, and where N number of turns this equation becomes equation 5.2. The area inside the loop is A in the equation, and I represents current. N is the number of times the loop is copied. The left hand side of the equation, μ_{coil} is the magnetic moment generated, and for this moment there is a requirement of $0.004 Am^2$

As long as the coil is stationary μ_{coil} can be treated as a scalar value, but it is a vector, which is normal to the current loop, with its origin at the centre of the area.

$$\mu_{loop} = I \cdot A \tag{5.1}$$

$$\mu_{coil} = N \cdot I \cdot A \tag{5.2}$$

From equation 4.3 it can be seen that it is advantageous to have a large area A and a large number of loops, N

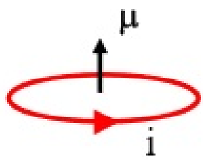

Figure 5.1: *diagram related to equation 5.1* [16]

in order to get a large magnetic moment. Increasing the current will also increase the magnetic moment but increasing the current will also increase power usage. In order to optimize for power usage therefore, N and A have to be converted into electrical resistance. That way the power efficiency can be found.

In order to improve efficiency the area has to be increased as much as possible. This area however has to fit inside the small volume allocated to the subsystem. The three orthogonal spools have to fit on the PCB shown in figure 5.2. Furthermore, part of the PCB has to be left open for other components.

The distance from the top of the PCB to the top of the coil is only 11 mm. This is too narrow for one of the coils to fit into the other. There are two options for crossing the coils. Wind them at the same time; this way the copper of one coil would be woven through the copper wires of the other coil. However this will complicate construction a lot. Another option is to wind them sequentially on the same spool, which has the drawback that one coils is stronger than the other.

In both cases if one coil would be damaged the other coil cannot be used. For that reason it was chosen to create a system such that each coil could be constructed independently and then be put together. This is one of the first design decisions made, and it has a profound impact on the eventual design and performance of the torquers.

If necessary it could have been possible to gain more area by integrating all three axis into one piece. But as mentioned it was chosen to use a modular design so that each coil can be constructed separately. This is a lot easier than winding different coils on a single part. An early concept with three wire coils wound around a single support structure is shown in figure 5.3.

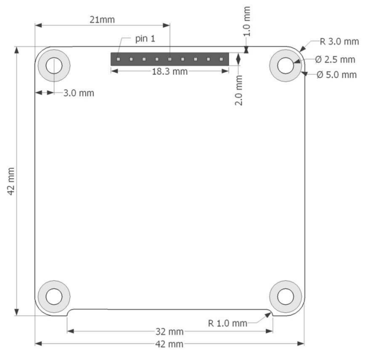

Figure 5.2: *External dimensions of Printed Circuit board for DelFi-PQ*

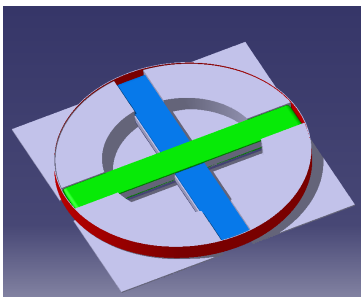

Figure 5.3: *Concept with all 3 coils on a single support, Blue is wound first, then green, then red.*

It was then chosen to put the in plane coil, the Z-coil around the outside and the X-coil and Y-Coil inside of the Z coil. This opposed to the possibility to have each coil occupy about a third of the PCB area. This choice was made since this gives the largest volume available per coil. This is in part because the Z-coil can double as a support structure for the other two coils. Also there is a requirement to leave part of the ADCS board free which is easier to accomplish this way. As a wire it was chosen to use the thinnest copper wire available. The wire is a solid copper of wire gauge 38. (AWG) By using thin copper wire more loops can be used. Another reason for this choice is that a thicker wire reduces resistance. Reducing resistance is a good thing, but there has to be a resistance in the coil because the voltage across the coil has a minimum value.

For the creation of the spool structure it was chosen to use 3D-printers. There were two options considered, CNC machining and 3D printing. It was considered that in order to create a machined piece, the CNC has only 5 degrees of freedom, requiring two CNC runs. The reasons for choosing 3D printing are speed, more flexibility in shapes and cost.

The reason that 3D printing was chosen is that it is possible to order 3D printed aluminum parts. While in the end the chosen material is different, aluminum is the back up option. Initially it was the intention to use bolts to secure the spools. However after some consideration it was decided to take advantage of the ability of the 3D printer to print any shape and connect the structure without bolts. Instead of being bolted to the PCB the structure is pressed onto the PCB by spacers. The X and Y spools will be designed such that they can only fit into the Z-coil structure from one side. If the Z-coil structure is then pressed onto the PCB the X and Y coils are automatically also pressed onto the PCB fixing them in place. In order to do this the tolerance between the Z-coil structure and the X and Y spools needs to be a tight fit.

While these choices determine in large part the way the system will look it still has to be optimized. In figure 5.4 a couple of iterations are shown. The final iteration uses the fitted joints while the first still use bolts. There were several more iterations, but they were more changes in sizing and tolerances due to optimization and in order to get a proper fit of the three components and not much different from the final iteration.

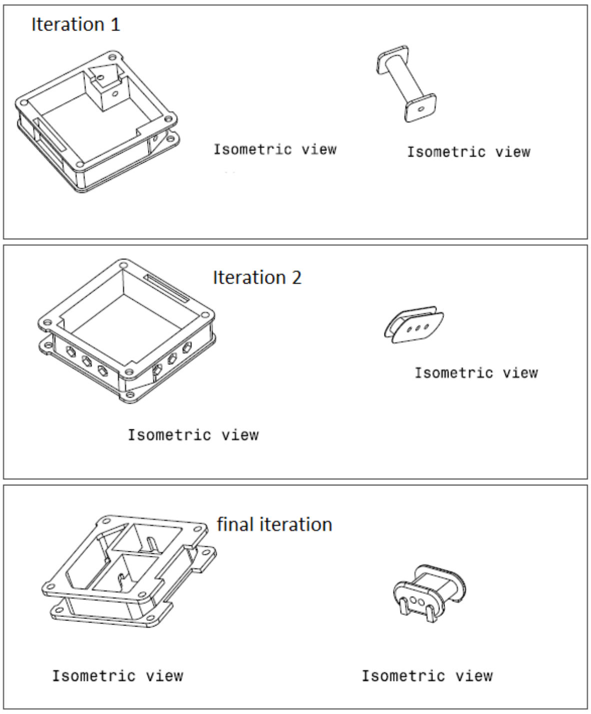

Figure 5.4: *Design iterations*

5.1. Design and Optimization

After deciding on the layout, the wire and the construction method, the spools were sized for optimum efficiency. The spools are also sized to achieve the goal of generating a magnetic moment for the given power. The volume constraint has to be taken into consideration as well. Moreover ease of assembly and construction must be guarded. In order to achieve this the Z coil was designed first. The shape of the Z-coil is dictated by the PCB, and especially the connectors on the board.

The internal area of the Z coil is then used to place the X and Y Coils. Then all three coils are optimized. Optimization is done on a parametric design of the coil. All design parameters are automatically adjusted to each other in a Matlab Script. The script is then used to plot the torque and power consumption across the design space.

In order to size the spool, an optimization run was done, running through the value d, which determines the number of loops that fit on a single layer the of the coil. It is important to note that the other dimension of the spool decreases when d is increased. This is because the spool on the other axis has to grow in the opposite direction. At d = 25 mm the spool is circular instead of the shape shown. At that point d cannot be increased any further. Comparing the Matlab script output with a circular spool was used to verify the accuracy of the calculations. The resulting optimization is shown in figure 5.5.

As can be noted from the second optimization run there is an optimum with respect to power around d= 12. Therefore the design is modified again to take advantage of this result. Another change that was made relates to the smoothness of the curve. As can be seen in figure 5.5 especially the resistance is a jagged line. This is because the spool is widened and shortened at the same time, however, if it is not wide enough to have an additional winding compared to the last data point, but it does get shorter, the wire length decreases. In figure 5.6 every data point d is chosen such that it can accommodate an integer number of winding's. It will have to be proven in practice that it is possible to wind as tight as assumed here. It may be necessary to widen the spool a little more to fit the design length of copper onto it.

Comparing figures 5.5 and 5.6 it can be seen that the location of the optimum has shifted somewhat. This is because it was realized that if the spools are only 3 or 4 mm wide, it would be sufficient to fix them to one side. However if they become wider it is important to have structure on both sides of the spool to withstand launch vibrations and loads. It is important to note that no load calculations have been performed, however experience with design of structures suggests that a mass (in this case the copper) attached to a cantilever structure (the spool) will suffer worse displacement due to vibrations if the cantilever is supported only on one side, and when the cantilever gets longer. Because the additional structure will take up volume the length of the spool has to be reduced a little bit.

For clarification, in the previous section length of the spool is the dimension that determines the length of a single loop of wire and the width of the spool determines the number of loops. However this is not all. There is another optimization parameter in this design. Namely the interior diameter of the spool. This has a minor effect on the performance but it is important enough to estimate what is best. Therefor this is included as an extra axis in figure 5.7. The red dot shows the optimum size of the spool possible within the constraints. However this is for a very good fill factor. As the fill factor decreased the inner diameter was reduced to increase room for the wire.

Another important thing is the temperature of the spool. As the resistance of copper is temperature dependent, the resistance will increase in a high temperature situation. The satellite will have solar panels on most sides. Therefore since the mass is low when it is on the sunlit side of it's orbit it will heat up quickly and it will cool down quickly when in eclipse.

The satellite orbit will experience eclipses. It is also possible that the inclination is not sun synchronous in which case the sunlit duration of the orbit may vary over the satellite lifetime. Also the surface finish of the radiating parts of the satellite may degrade over the lifetime resulting in temperature differences.

Furthermore if the rotational rate of the satellite is low with respect the rotational rate of the orbit, the satellite will have a hot face and a cold face. The copper wire itself is an excellent conductor of heat, therefore it is likely that the temperature gradient will be low, however, if the temperature on the cold side gets relatively high the temperature gradient may be large as well, because of the increase in effective thermal radiation from the cold side.

Because of all these reasons it is important to verify if the design optimum is the same at high temperatures, e.g. 60 degrees C and low temperatures, e.g. 0 degrees C. It turned out that the temperature does not effect on the optimum design point, however it does influence performance. This influence can be seen in figure 5.8. The design here was optimized, and then a constant voltage was selected to produce the required torque at 20 degrees Celsius, which is the normal operating temperature. Because the temperature increases the resistivity of the copper wire increases and thus the current decreases. If it is possible to match voltage and temperature, the required torque can be achieved by increasing the voltage, and thus keeping the current constant despite increasing resistance.

Especially in eclipse the temperature will drop rapidly and when in full sunlight it may get very warm. Because the satellite is small it does not have a large heat capacity and may heat up and cool down quite rapidly. The effect of the the temperature has to be taken into account. Either the controller gain has to adapt to the temperature or the voltage has to adapt to the temperature. If the second option is selected the control system can always assume the gain is constant. Otherwise controller has to change the actuation times based on a temperature depended gain. If the voltage adapts to the temperature the effect of the temperature on the performance is shown in figure 5.9. As can be seen the temperature will have a significant effect on the performance.

5.2. Construction

In order to construct the spools for the prototype a 3D printer was used. The printer was the Ultimaker 3. The advantage of this printer is that it can print two different materials in the same print. By using a water soluble printing material as one of the materials it is possible to print any shape, without having to limit overhang. This makes it possible to produce almost any shape.

Printing mechanical parts comes with the challenge of maintaining enough tolerances throughout. For this reason the design was modified to take into account a tolerance of 0.2 mm all around. The printing material is soft when it is printed. Therefore it deforms about 0.2 mm after it has been printed. Through trial and error a good fit of the different components is attained. A render of the resulting design for the spools can be seen in figure 5.10. With this tolerance taken into account the spools fit very well into the structure. Construction drawings for the spools are included in appendix D

5.2.1. Winding

After printing the spools copper wire was wound around them to form the coils. This is a very delicate procedure and the first attempts produced a very poor result. In order to facilitate the winding process a winding apparatus was made. A picture of the winding apparatus is shown in figure 5.11. This apparatus consists of a 3d printed support for the spool, which is connected to a stepper motor. The wire is fed from the spool it arrived on from the wire manufacturer. The stepper motor counts the number of revolutions and can be controlled with a foot pedal. This leaves the operators hands free to guide the wire using a pulley. Using pair of tweezers winding defects were reduced. Tension in the wire was created by friction resistance on the feed spool and the action of the stepper motor. The wire on the feed spool was very loosely wound, hence creating uneven tension in the winding process. Tension was increased or decreased by adjusting a screw to create more or less friction.

The connection between the stepper-motor and the spool is a 3D printed mounting piece. This can be seen in figure 5.15. This piece can also be used to tape the wire down. By taping the wire to the rim, tension can be put on the wire.
Due to issues with the winding process, the spools had to be redesigned several times. The wires have a circular shape. When fitting a number of circles in a rectangular shape the area of the circles is always less than the area of the rectangle. The optimal packing of the wires onto the spool is found by orthocyclic winding. This has a theoretical fill factor of 90.7 %. The fill factor is defined as the area of recesses in the spool divided by the cross-sectional area of all wires that are wound onto the spool. A schematic representation of the orthocyclic wire is given in figure 5.12. In practice it was attempted to approach this by a helical winding process, winding the first layer from right to left and then the second layer from left to right and so fort. Each subsequent layer is guided by the previous one. From the start it was expected that the winding would not reach the theoretical optimum. However it was found that for many layers, such as is used in this design it is very difficult to prevent the helical winding to shift into a wild winding. While the first 3 layers were generally close to orhocyclic, adding more layers would cause wires alternate between layers. For example when adding layer four, somewhere in layer 2 or 3 enough room to move still remained meaning one of the layer 4 turns was pressed into layer 3. This then reduces the self-guiding of the wire. It is thought that defects of this kind may be substantially reduced with increased wire tension.

It is planned to find a different wire winding machine for the flight model. Purchasing a wire winding machine only for Delfi purpose is too expensive. It is hoped that a commercial company or other university department has a suitable winding machine. Due to the small wire diameter this may be difficult. Improve the winding apparatus could also be a possibility. In order to improve the winding quality at least the following has to be done:

- Rewind the wire on a different spool. The manufacturer has wound its spool very loosely. Therefore it cannot be used when tension in the wire is increased.
- Add a mechanism to create a uniform tension in the wire that is maintained throughout the process.

- Replace the stepper motor with a more powerful variant to overcome increased tension.
- Improve the wire guide. Either through computer guidance or through a manually operated mechanism.

A wild winding has substantially lower fill factor. Therefore the spools were redesigned to accommodate a wild winding. During the construction it was found that the fill factor was even poorer than expected. This will result in a lower torque. In the design there was some additional area on the spool as a margin of safety. In the prototype this extra area was filled which meant that the targeted torque could be reached. The poor fill factor is the result of the very thin wire gauge and a lack of control on the tension in the wire while winding.

5.2.2. Construction Result

The final version of the prototype was printed according to the specifications in the drawing. The prototype was finished and prepared for testing. The construction proved more difficult than expected. The achieved fill factor was quite low. The fill factor is a measure of how well the coil is wound by comparing the open space in the coil compared to the space filled with copper. It is expressed in percentage and the maximum for round wires is somewhere near 90 % filled with copper. The lower fill factor of the wire changed the properties of the

result	resistance [Ω]	fill factor [%]	turns	turns planned
z-coil (red)	34.72	49	244	244
x-coil (blue)	30.96	51.9	725	872
y-coil (green)	33.87	63.9	800	872

Table 5.1: Construction quality prototype 1

prototype slightly compared to the design point. The most important differences are shown in table 5.2. Due to the lower fill factor the number of turns is reduced but the wires are also further from the center of the spool increasing the magnetic moment. In the table the coils are indicated with red, blue and green, corresponding to the colors in 5.13.

blue	Design	Construction	unit
turns	872	725	
resistance	32.12	30.96	Ω
d	10.69	10.70	mm
inner diameter	5.00	5.10	
n	0.08	0.06	
green	Design	Construction	unit
turns	872	800	
resistance	32.12	33.87	Ω
d	10.69	10.70	
inner diameter	5.00	5.10	mm
n	0.08	0.07	
red	Design	Construction	unit
turns	244	244	
resistance	32.12	34.72	Ω
magnetic moment	0.0166	0.0170	Am^2
n	0.28	0.29	

Table 5.2: Construction quality prototype 1

5.3. Material

The material that is used in 5.13 cannot be used in space. The reason is that the material does not perform in a vacuum. Another material that could be used is PEEK or polyether ether ketone. PEEK is a semicrys-

component	number	mass	unit	material
spools	2	1.45	gram	Ultem-9085
support	1	6.374	gram	Ultem-9085
wire	3	5,9	gram	Insulated copper
PCB	1	8.3	gram	FR4
fitting	1	1	gram	est.
total		36	gram	

Table 5.3: Mass of the system when completed.

talline thermoplastic with excellent mechanical and chemical resistance properties that are retained to high temperatures. The processing conditions used to mold PEEK can influence the crystallinity and hence the mechanical properties. Its Young's modulus is 3.6 GPa and its tensile strength is 90 to 100 MPa. PEEK has a glass transition temperature of around 143 °C and melts around 343 °C. Some grades have a useful operating temperature of up to 250 °C. The thermal conductivity increases nearly linearly with temperature between room temperature and solidus temperature. It is highly resistant to thermal degradation, as well as to attack by both organic and aqueous environments. It has high resistance to biodegradation too. [26]

PEEK is very difficult to print however. Another material was found that is easier to print called Ultem. Ultem is the trade name for polyetherimide (combination of Vespel and PEEK). Ultem is like PEEK, but has better adhesive properties and stability. Polyetherimide (PEI) is an amorphous, thermoplastic. PEI is cheaper than PEEK, but is lower in impact strength and usable temperature. Because of its adhesive properties and chemical stability, it became a popular material for FDM 3D printers. The molecular formula of the repeating unit of PEI is $C37H24O6N2$ and the molecular weight is 592.61 g/mol. Ultem 1000 is the unfilled product, other grades may have additives. 9085 grade and 1010 grade are offered for 3D printing specifically. Ultem 9085, High flow Polyetherimide blend, meets FAR 25.853 and OSU 65/65 with low toxicity, smoke and flame evolution[27]. The printing temperature of Ultem is very high and cannot be achieved with the Ultimaker printer. Fortunately there are several commercial companies that provide printing in Ultem at a good price.

5.3.1. Mass

The mass of the system is quite easy to determine given an very accurate scale. The results from the measurement are given in table 5.3 The PCB weighs (not populated) 8 grams for 4 layers, and 10 grams for 8 layers. This was not measured even though it was included in the table, but is given by the PCB manufacturer. The total weight of the system is 36 grams.

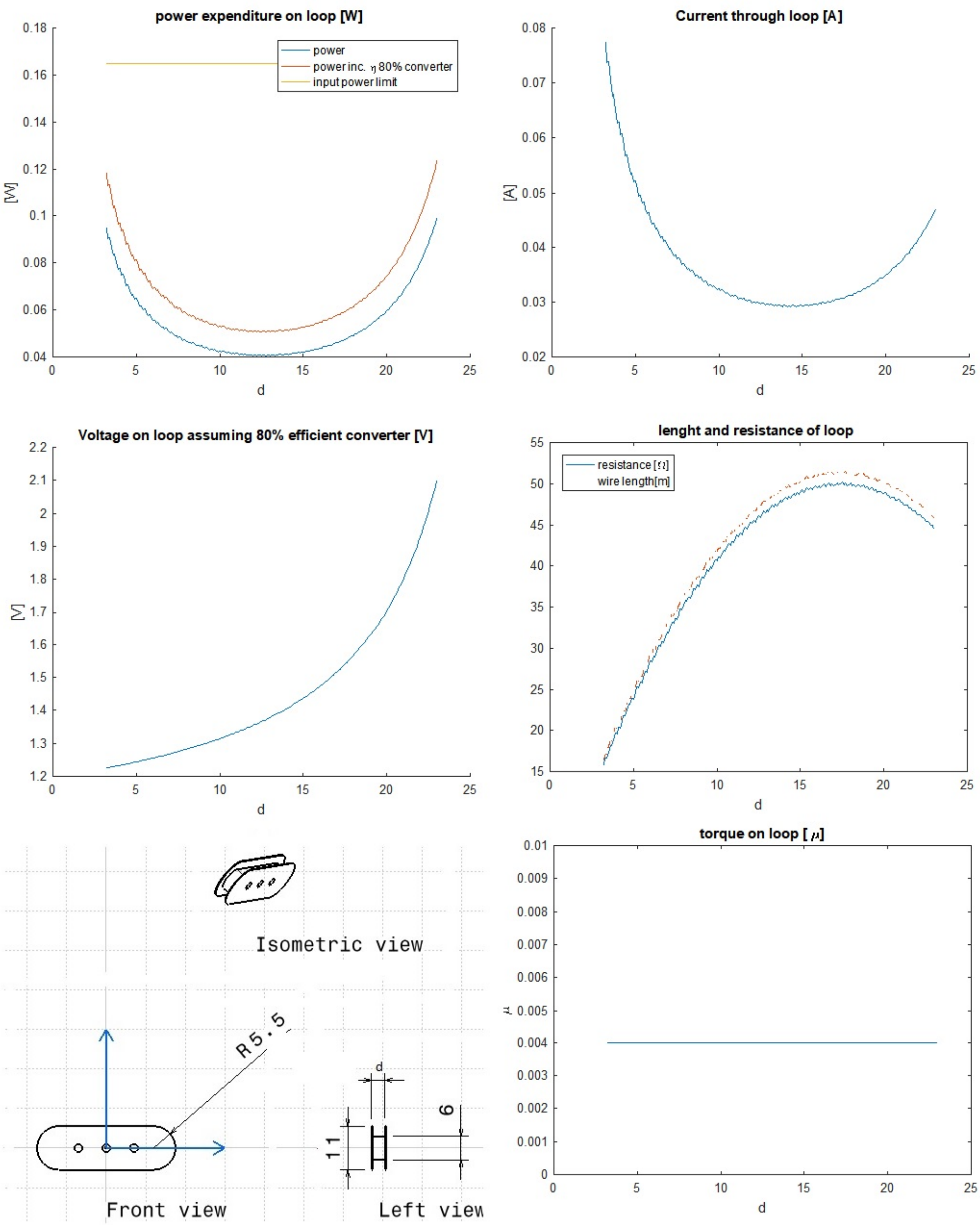

Figure 5.5: *Optimization for power*

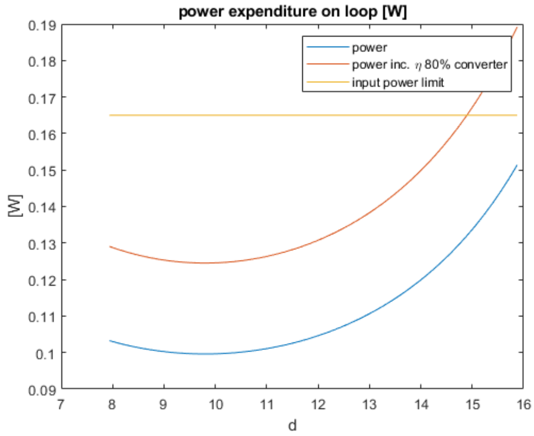

Figure 5.6: *Optimization for power for the second to last iteration.*

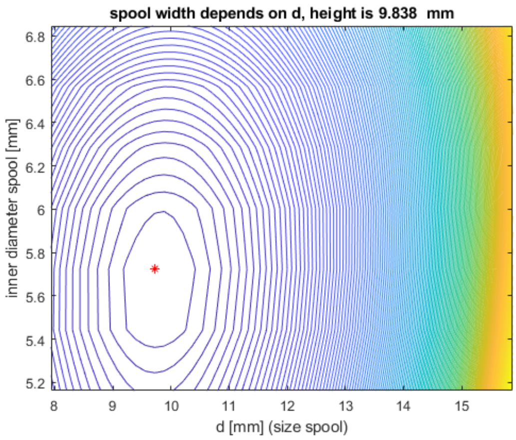

Figure 5.7: *Optimization for power for the second to last iteration.*

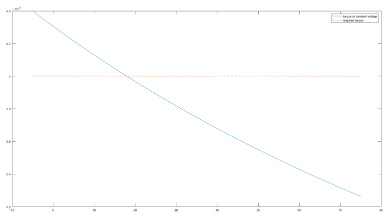

Figure 5.8: *Effect of temperature on performance at constant voltage*

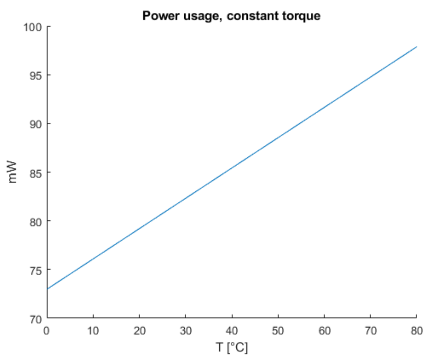

Figure 5.9: *More power is required if the temperature of the coil increases.*

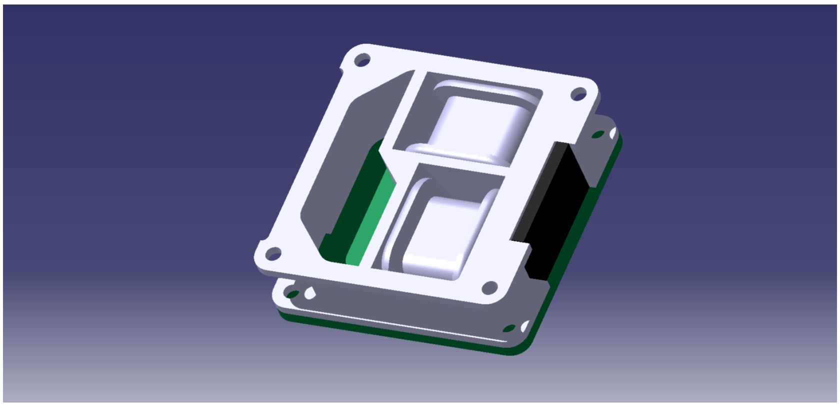

Figure 5.10: *Render of Final Design*

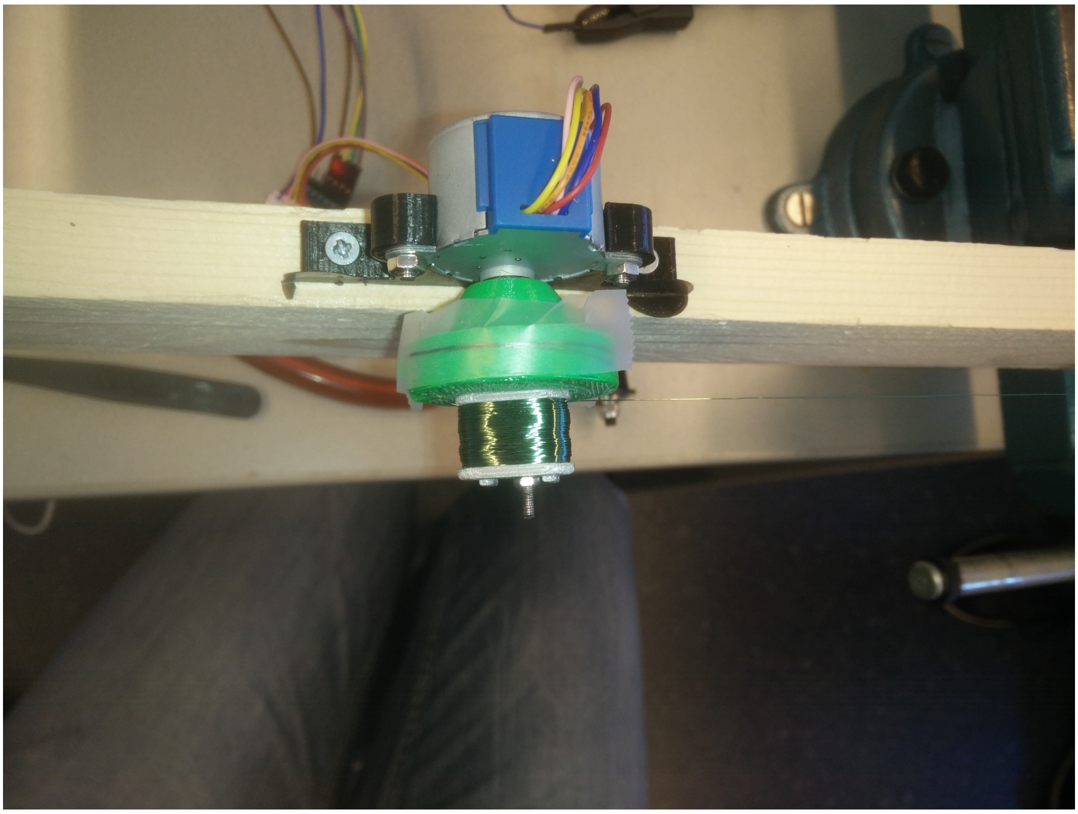

Figure 5.11: *Winding Apparatus with coil after winding*

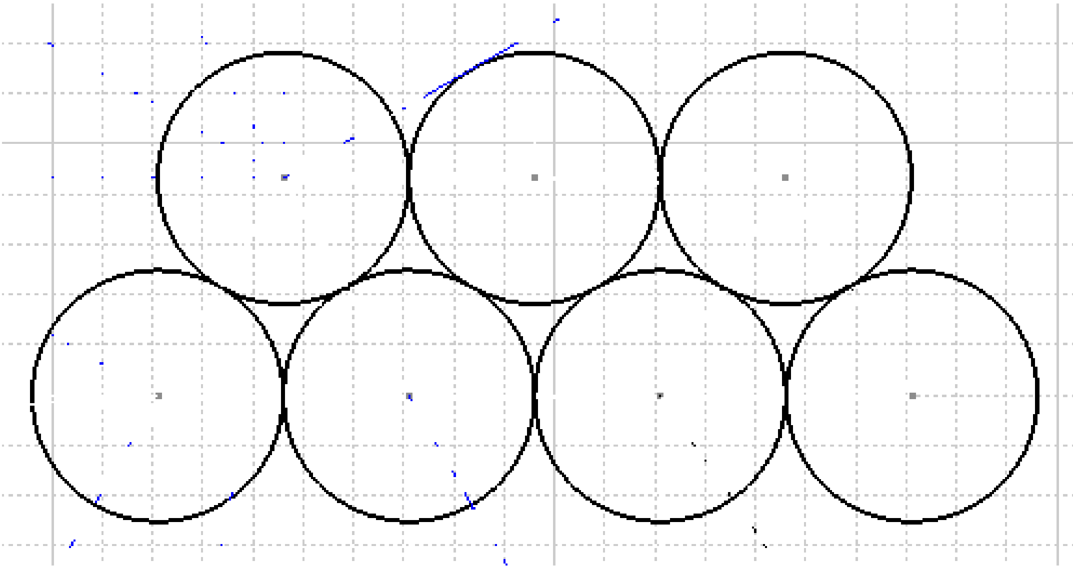

Figure 5.12: schematic representation of orthocyclic winding

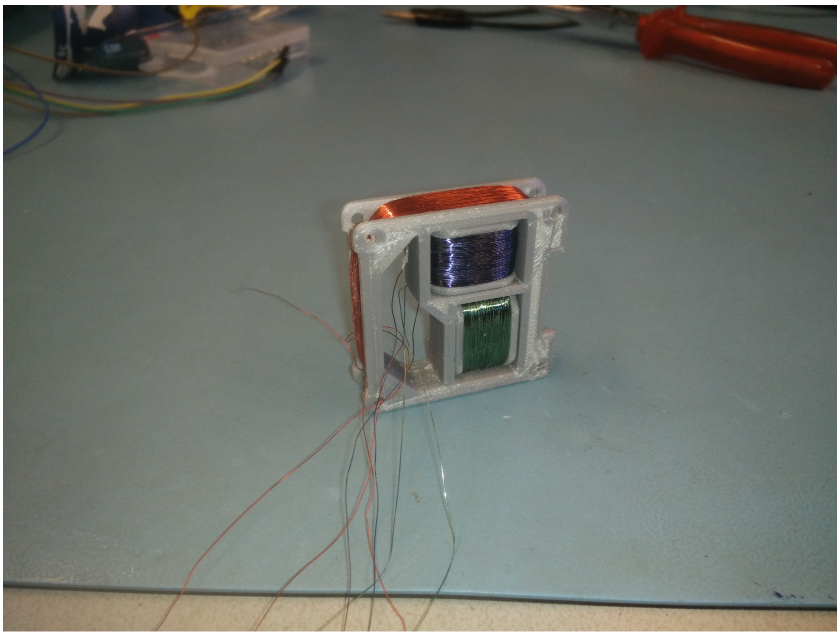

Figure 5.13: *Prototype 1*

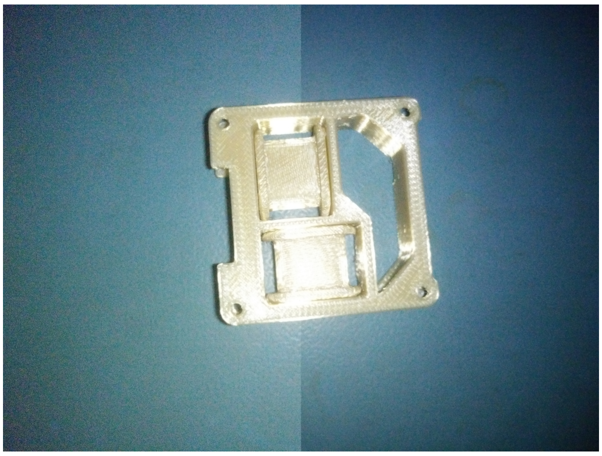

Figure 5.14: *Ultem Prototype, printed by Materialise*

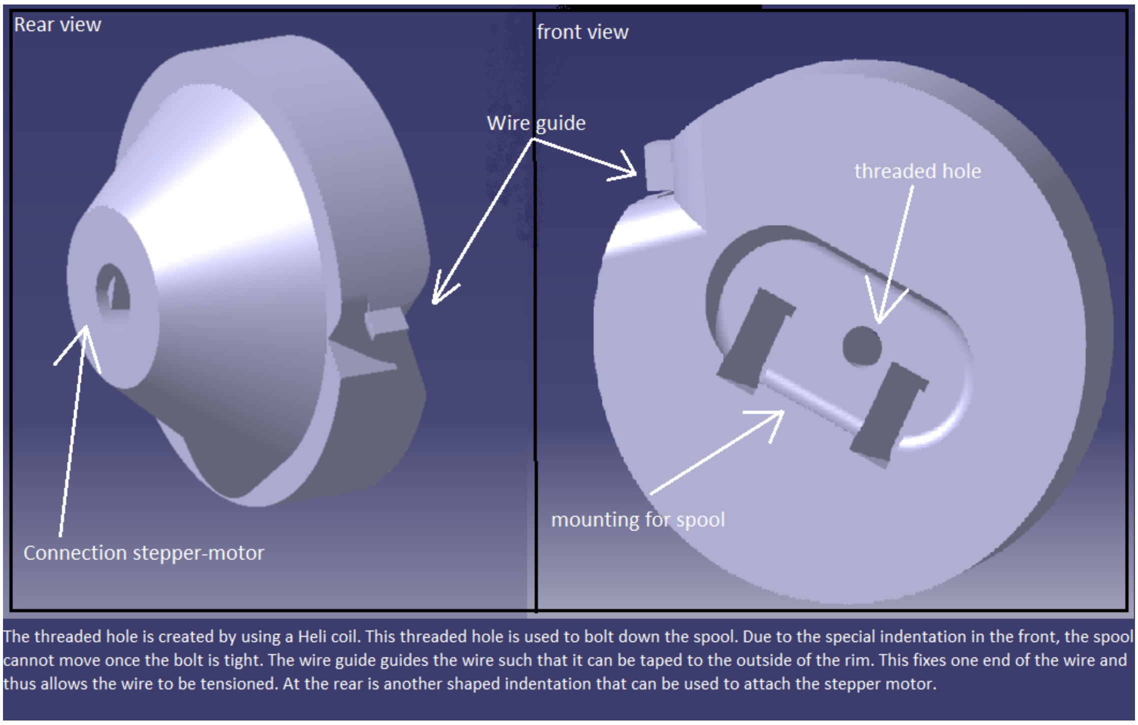

Figure 5.15: *This piece is used to connect the spool to the stepper motor and hold one end of the wire*

6 PCB Magnetorquer

One of the easiest ways to lay out copper is the use of PCB production facilities. In order to do so PCBs, printed circuit boards, are produced in batches by specialized suppliers. They are able to produce almost any shape and depth of PCB. In development of DelFi-PQ this manner of construction is used extensively. In the same fashion a set of PCB's was created with the coil already embedded. Some PCB nomenclature is explained in the Glossary and Appendix A

In this case it was chosen to use four layer PCB's. It is possible to profit from the ability to produce more layers in order to introduce the PCB coils into boards whose surfaces are already mostly in use. In principle PCBs can be produced with as much as sixteen layers, but cost increases with each extra layer.

In order to have a starting point, similar goals were set for this design as for the air-coil for DelFi-PQ however, they are not requirements, and they can be deviated from in case necessary. As can be seen from the list they are less restrictive in the application. The torque and power requirements are retained, as there was no better estimation of the required capability at the start of the design process.
It is thought by the Delfi-PQ team that power consumption will be the most important constraint on the usage of the magnetorquer. It therefore needs to be optimized with respect to power usage. When putting the coils in the PCB the volume use is not an issue, because the PCB has to be there anyway. It could mean that the PCB would become slightly thicker.

However, in order to place the PCB the entire satellite has to be taken into account. The attitude control PCB can only contain one actuator coil. The other two axis require two more printed circuit boards that are placed orthogonal to the attitude control board and each other. Therefore it is less easy to connect the entire subsystem, as the attitude control board must control all coils, but the coils cannot be all put on that board. Therefore the attitude control board must control coils in other parts of the satellite. Normally these other PCBs will have another (primary) function too.

In the case of DelFi-PQ the walls of the satellite are built out of PCBs therefore the PCBs are available. Furthermore the interior PCBs are oriented orthogonal to the walls. In the general case of PocketQubes the bottom wall is always present, as per the PocketQube standard, so another PCB can be put there. In some cases, where the side walls fold out to increase solar panel area, a PCB containing the third axis will have to be added specifically.

The design principle can be compared to chapter 5. All concepts and formulas mentioned there apply here as well. The way the system is constructed is very different however. The Z-axis coil will be integrated in the PCB that is shown in figure 5.2. In addition to this coil there will be two coils in the side walls of the satellite. Since the sidewalls are larger the design of the Z-axis coil is the most difficult. This is in contrast to the wire coil design where the x and y axis were more difficult, because those axis had less internal area there.

The board should be powered from the connector at the top, as that is the standardized connector to the satellite. Furthermore, the coil cannot go through on the holes in the corners of the board. In addition to this there can be no vias where the coil traces are.

The coil was designed using the rules for PCB's from Eurocircuits. The idea is to lower the voltage as much as possible. With a low voltage the current can be higher for the same power. The minimum voltage is given by the switching converter.

If the voltage is low the resistance of the coil has to be low. A low resistance means a wide trace, however a wide trace means that the internal area will be reduced. If the internal area is reduced too much it is better to add extra layers.

A render of what the full system should look like is shown in appendix B. This is a cut out of a 3U PocketQube with anything that is not part of the magnetorquer system left out. There are also four aluminum rods that represent part of the structure of the satellite in the render. In reality the traces would not be so visible. The choice could be made to have a coil in all the walls or in just two. If the coil is in all the walls the coldest walls should be activated, because the coil resistance increases with temperature.

6.1. Electrical Design

Because the board is actually built the electrical design has to be fully completed. In order to do this use is made of a software called Autodesk Eagle, which is a computer aided design tool for PCB's. Eagle has the possibility of writing small programs that does much of the work automatically. One of the issues with using the program is that it is not created to produce coils. Drawing the traces by hand is a lot of labor and every time the design is changed, this work has to be done again.

The possibility write code for Eagle helps out in this respect. A code written to create to coils can also automatically calculate the length and area of the coil. Calculation of the Area is another problem that is difficult to do by hand because each loop has a slightly different area. Therefore this code is very handy when designing a coil for a PCB.

In addition to the coil also the switching converter is added to the PCB. This is consistent with the use case in the satellite where the switching converter would also be on this PCB. If the design were to be used for a flight model, most probably the micro controller for the ADCS system would also be on the PCB however it was chosen to leave the other components of the board because that makes it easier to test.

The electrical schematic is shown in figures 6.1 and 6.2 and 6.3, where the current sensor, the converter and the connectors are depicted.

6.2. Switching Converter

In order to be able to select the desired voltage a switching converter is used. This is one of the most efficient ways to create a DC-DC converter. The reason that selecting the voltage is desirable is that if the coil is connected directly to the bus voltage the efficiency will be poor. This can be seen from the following: the power of the coil is related to the voltage by equation 6.1 and the current is related to the voltage by 6.2. Since the torque is equal to $n \cdot I$, The efficiency of the coil, torque per power is then given by 6.3, on the assumption that resistance of the coil R and torque factor n stay the same, which is reasonable because they are functions of temperature, material and geometry of the coil. It is therefore desirable to reduce the voltage as much as possible to increase the efficiency of the coil.

$$P = \frac{V^2}{R} \tag{6.1}$$

$$I = \frac{V}{R} \tag{6.2}$$

$$\eta_{coil} = \frac{n \cdot I}{P} = \frac{n \cdot \frac{V}{R}}{\frac{V^2}{R}} = \frac{n}{V} \tag{6.3}$$

Reducing the voltage has to be efficient however otherwise the efficiency gained in the coil will be lost in the voltage conversion. This can reduce the output voltage with an efficiency as high as 95%. In addition to this, the converter has the advantage of providing a more or less constant output voltage, even when given a

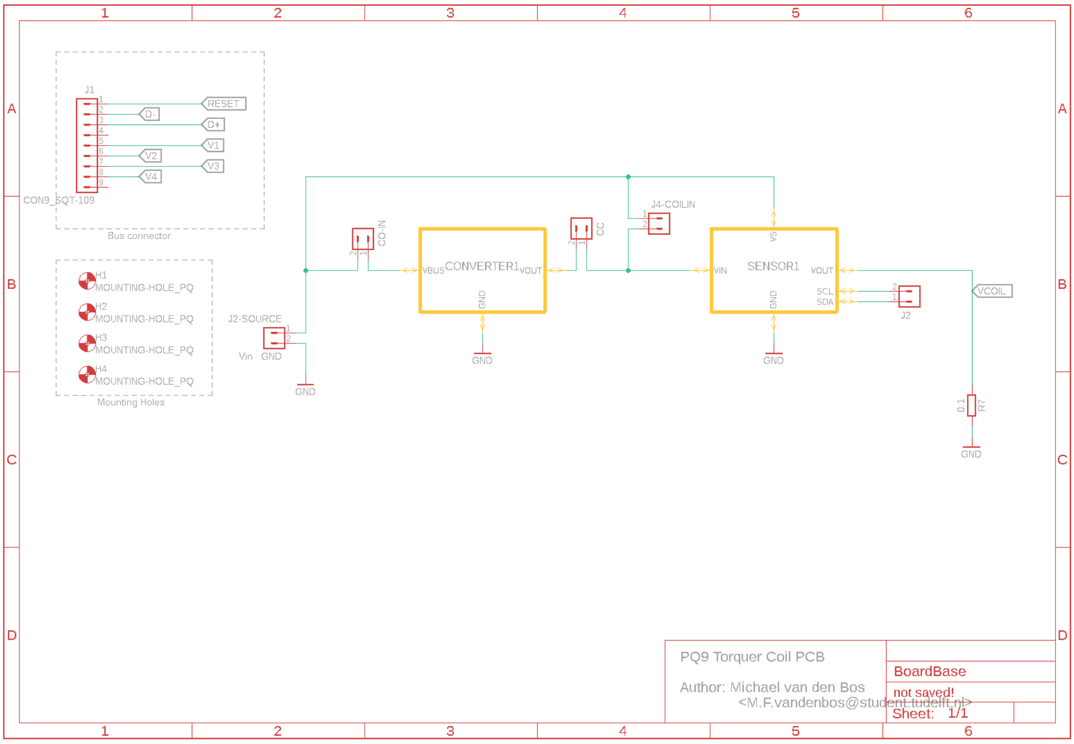

Figure 6.1: Schematic PCB coil

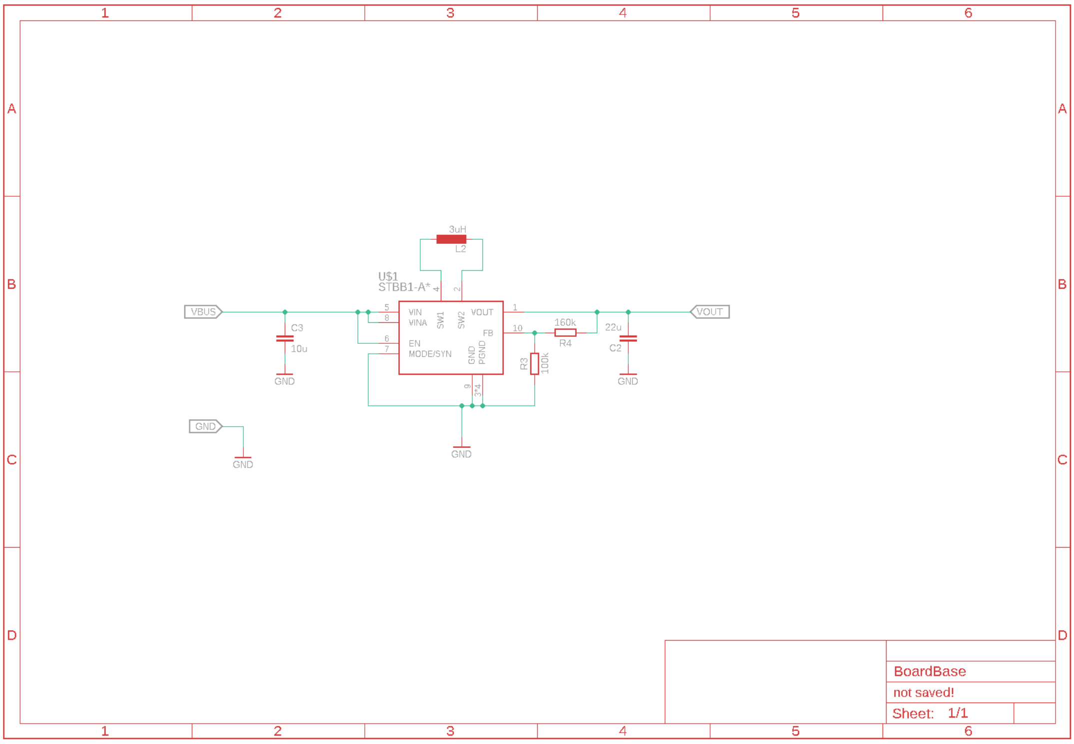

Figure 6.2: Schematic Switching converter

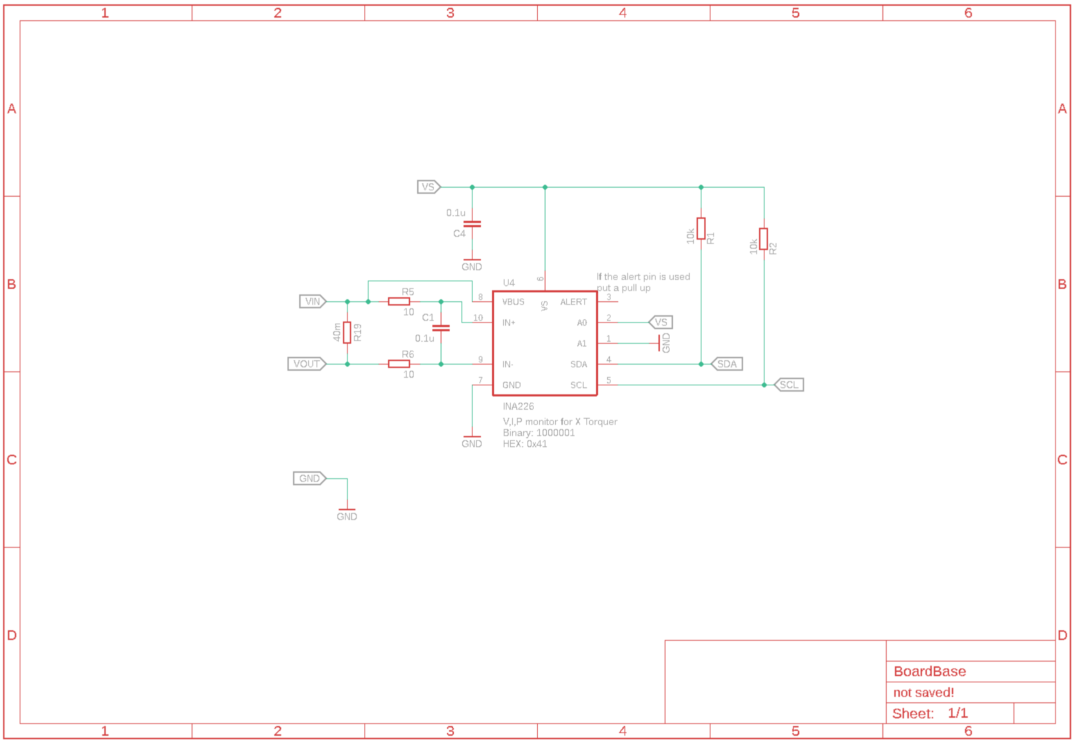

Figure 6.3: Schematic current sensor

changing input voltage. Therefore the circuit will provide a similar torque at low battery charge and at high battery charge.
Unfortunately the converter efficiency is dependent on the output voltage. At lower output voltages, the efficiency tends to drop off. Furthermore there is a practical limit for the switching converter. This depends on the device being used, but most devices will require a certain voltage to power the switches.

Device selection and margin of safety will determine the lowest possible output voltage. Selection of the switching converter for the flight model was done outside the scope of this thesis and may contain other selection requirements which have led to the component selection. The switching converter chosen was the STBB-1APUR which can be used in either boost, buck or buck/boost modes.

The efficiency of the device is given by the manufacturer for several use cases, see for example figure 6.4. Unfortunately this cannot be translated directly to the use case, where V_{out} is below 2 Volt and V_{in} is between 3.0 and 3.6 Volt. The closest is the blue line which is approaching 75% on the far left. Therefore it may be assumed that the efficiency may be lower at the targeted output.

6.3. Calculation of Switching Converter Efficiency

The following is adopted from Texas instruments and RHOM semiconductors. [29], [30]. It is here assumed that the dependencies are the same for for products of other vendors. There is a discrepancy based on the design and nature of the devices. For example TI has different high and low side switch resistances. For the STBB-1APUR both sides use the same switches and have the same resistances. Naturally the calculations have to be confirmed by testing.

Based on the calculations the following is found. The efficiency rises with power, if the power required is lower, the efficiency drops. This is because the IC or other loss component is kept constant in the calculation. It is important to note that the efficiency is also very dependent on the components that are included other than the switcher itself. (the inductor, and the capacitors primarily.)

Unfortunately it was found that the size of the inductor would have to be very large in order to run the con-

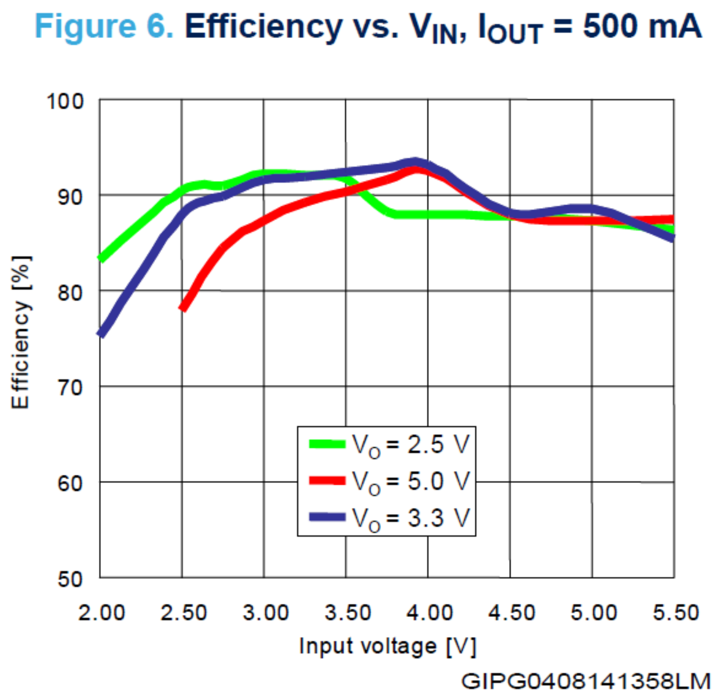

Figure 6.4: STBB-1APUR efficiency [28]

verter in continuous mode. This is because the inductor has to greatly resist the voltage rise. Increasing the size of the inductor would massively increase the resistance in the inductor. However the STBB-1APUR can also run in discontinuous mode, while using a small inductor. It was therefore decided to run the converter in discontinuous mode, because the large inductor would decrease the efficiency too much. The drawback of this is, that the current will be less constant. Because the coil itself also has a large inductance this will negatively effect performance. Testing will be required to determine the effectiveness of the system using the switching converter like this.

In order to reduce the drawback it may be possible to increase the capacitance of the circuit by increasing the capacitor. The converter should then produce a larger current, increasing the charge in the output capacitor. This is then discharged through the coil.

This specific converter was chosen because it is the converter that is intended to be used on other subsystems of Delfi-PQ. This converter is a buck boost model which is used a lot for applications where a steady voltage is required and the power supply gives a unsteady voltage. The objective was not to design a perfect switching converter as this is better left to an electrical engineer. However the switching converter will influence the result to a large degree. It was therefore chosen to include it in the design because it is important to see the complete picture of the electrical system. The switching converter output will behave different from a power supply. Furthermore, the switching converter has to be to be combined with several components to be able to do its job. The most important are a inductor and a voltage divider. The voltage divider will determine the output voltage. This can be tailored to the coil.

Because the torquer coil itself is also an inductor, the inductor of the converter and the coil may affect each other. That is another reason to test the coil with the converter.

6.4. Calculation of Efficiency

As mentioned semi empirical formulas are used to calculate the switching converter efficiency. The efficiency depends a lot on the inductor used, but also on the electrical characteristics of the device chosen. The STBBB-1APUR[31] datasheet gives a few examples where the efficiency can be calculated.

Based on these examples an efficiency can be calculated for another operating point. In order to do so information from the data sheet is used to evaluate a number of semi-empirical formula's from the Rhom document. [30]

$$P_{ON-H} = I_{OUT}^2 \times R_{ON-H} \times \frac{V_{OUT}}{V_{IN}} [W] \tag{6.4}$$

$$P_{ON-L} = I_{OUT}^2 \times R_{ON-L} \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right) \tag{6.5}$$

$$P_{SW-H} = \frac{1}{2} \times V_{IN} \times I_{OUT} \times \left(t_{r-H} + t_{f-H}\right) \times f_{SW} \quad [W] \tag{6.6}$$

$$P_{SW-L} = \frac{1}{2} \times V_D \times I_{ou\tau} \times \left(t_{r-4} + t_{f-L}\right) \times f_{SW} [W] \tag{6.7}$$

$$P = I_{OUT}^2 \times DCR \tag{6.8}$$

Equation 6.4 gives the conduction loss in the high side switches as function of the in and output voltages and the output current. R_{ON-H} is the resistance of the switch. This value was found in the datasheet. Equation 6.5 gives the same loss for the low side switch. Because the datasheet has only one switch resistance value it is assumed that both sides have the same resistance. Equations 6.6 and 6.7 give the losses related to the switching of the switches. This is dependent on the switching frequency (f_{SW}) and the rise times (τ).

The loss by the inductor is given by 6.8 where DCR stands for inductor direct current resistance. For a small inductor this is very low, but for larger inductors this value climbs very quickly. These losses are dependent on the current, and the in and output voltages. In addition to these losses there is a certain amount of power required to operate the device itself. This is given in the datasheet as maximum 5 mA, this multiplied by the input current of about 3.3. V gives a operation power of 16 mW.

There are a few more loss factors described in the article but they are not as dependent on the operating point of the converter. Adding all the losses together should give the entire loss of the switching converter. When this loss is compared to the efficiency in the examples given in the datasheet, it became clear that the losses were underestimated by about 25%. Therefore the difference between the example and the calculated loss is taken as another constant loss. These high constant losses cause the efficiency to drop when the output power is decreased. It is not known what is causing the additional loss compared to the theoretical loss. It is therefore not known if this additional loss may be influenced by in and output voltages, or the current through the device.

For the air core magnetorquer the wire thickness is fixed. It is possible to increase wire gauge, but the resulting resistance would be too low. Therefore the optimization for the air core is done without taking the efficiency of the switching converter into account. The voltage is then decided based on the required current, after which the switching converter efficiency is taken into account to get to the final power requirement. For the PCB coil it was recognized that the resistance of the coil could be selected by varying the trace width. The switching converter was therefore included in the design.

6.5. Optimization

As mentioned, there are conflicting sizing requirements. At one hand the internal area has to be large, therefore the trace width has to be small, on the other it is good to have wide traces so that the resistance in the traces is low.

In addition there is a possibility to increase the number of layers. This cannot be done indefinitely. The practical limit of layers is 16. However this also results in a thicker PCB. The main problem with many layers is the the cost. A secondary problem is that the more layers are on the board, the more vias are needed.

Another thing of importance is the efficiency of the switching converter. If the converter maintains a high efficiency, the efficiency of the coil determines the efficiency of the system. However most switching converters lose efficiency if the difference between the input and output voltage increases.

Therefore, when lowering the coil voltage the coil efficiency increases while the converter efficiency decreases. It is therefore important to model the switching converter as well.

This was not done for the wire coil, because the wire thickness could not be changed as easily. Therefore, there was no real method to affect the resistance of the wire, since the thickness of the wire is a given. Using a thicker wire would cause the number of loops to drop off so drastically that the current would be increased too much. Of course, the performance figure of the wire coil also drops if the switching converter performs poorly.

For the case of the PCB there are etching limitations as well. It is therefore harder to simulate the PCB coil without drawing the coil accurately. Therefore coil drawing code that was developed to draw the traces also automatically calculates the trace length and internal area of the coil.
Of course it would have been nice if the code would automatically optimize internal area, but developing that capability took too much time for this graduation assignment. Therefore the shape the code draws is hard coded. This means there is still some room available to improve utilization of the area available on the board. Therefore it is possible to optimize the board even further.

It was also chosen to use rounded edges as much as possible. When creating traces on a PCB it is better to not use 90 degree angles in the traces because this has a detrimental effect on the current, increasing resistance. Electrical current is comparable to water in many cases. A water pipe does not work well with 90 degree angles, it uses rounded bends. In PCB design it is common to use 45 degree angles, but it is even better to use rounded corners. Defining corners for every trace would be too time consuming, use too much valuable board area and provide only very marginal improvements over a corner consisting of two subsequent forty five degree angles. In this case however, since the resistance of the coil is important, and the trace is defined by a code anyway, it is better to use rounded corners where possible.

This coil drawing method was used several times to get several cases. The required voltage is then calculated for each case, as is the magnetic torque and power. Combined with the model for a switching converter efficiency, the overall system efficiency is then calculated. The trace width the best overall system efficiency is then chosen. If the requirements are not met, the number of layers is increased.

Eventually a design with four layers was found that would satisfy the magnetic moment requirement. It also satisfies the maximum power requirement. The coil is etched onto all four layers. The internal area of the board is used to place the switching converter. The switching converter cannot be connected to the PQ bus connector, because the coil is blocking the traces on all four layers.

The reason for choosing four layers is that having a four layer PCB is less costly than a six layer PCB. If a 6 layer PCB would be constructed, it could be connected with the PQ bus connector. If the coil were to be included in the ADCS board, the PCB would most likely need eight layers, because the ADCS board already uses four layers for the routing of all components. Furthermore the shape of the coil may need to be modified slightly to accommodate certain components. For the prototype board a couple of components have been left out. On a complete ADCS board there would be at least a second switching converter, a micro controller, several extra power measurement components, a number of resistors and capacitors, two additional connectors, control circuitry for the x and y coils and a magnetometer. It should be noted that there is room enough for all components on the PCB. However placing vias will be more difficult since vias cannot be placed on top of the coil. If the coil is in the internal layers there can be components placed on top of the coil, but no vias. It is possible to use blind vias, however using blind vias will increase the cost of the board.

The design is power optimized as much as possible. One of the things that will matter is the area of the board where the coil cannot be placed. The larger the area available for the coil the more efficient the coil can be made. However the area available is an estimation. Another thing is that there are many optimization parameters. More loops can be added to the coil, but they will be smaller. The resistance of the coil can be reduced by increasing the width of the trace. However the result is that the internal area is reduced. The current optimization method is chosen to be a trace width of 0.19 mm with a voltage of 1.3 V. Adding more loops may increases power efficiency. But that would increase the trace width, and reduces the area available on the board.

For the wall there is less optimization done. The resistance has to be the same as for the PQ-board. Otherwise the power efficiency can be adjusted. Since the resistance is fixed it becomes about the optimal combination of area and trace width. More trace width is more trace length and thus more area, more torque. Adding more loops with ever increasing trace width seems to improve power efficiency, even though each loop gets smaller. Another reason is that the efficiency of the power converter drops with low currents. The efficiency of the converter is included in the design using the method. Depending on the converter efficiency putting more current in the loop could be more efficient than creating more loop. The actual efficiency of the switching converter has to be measured.

The optimum was found by almost filling the board. The traces are wide, 0.5 mm and very many loops. The problem with filling the board is that like the PQ-Board the wall also has to retain space for other functions. If the resistance and voltage are the same, the current and power will be the same. The PQ-board would also be more power efficient if the entire area of the board could be utilized. But that is an unrealistic case. It is also not very realistic to assume the walls will have the entire area available for the coil. Optimizing the PCB coils is therefore more difficult than the wire coil. The optimization has to include drawing of the traces to check the viability of the design, when taking into account the other functions the PCB has to fulfill. For the purpose of the thesis the wall coil will be allowed double the trace width and thus double the trace length of the PQ board, but this may change for a real satellite, depending on the number of components placed on the walls, and the way the walls are used.

6.6. Construction

The coil is implemented as shown in figure 6.5, this shows the top view of the board.A similar view of the wall is shown in figure 6.6 It is a 4 layer board, meaning that there are four layers of copper beneath the layer shown. In total there are fourteen loops on each layer, hence fifty six loops in total. The peculiar shape of the coil is to maximize the area inside. However this may slightly deform the magnetic field. This is evident by calculating the centroid of the area. The magnetic moment vector is located in the centroid of the coil. However because the coils are not symmetric in all directions the centroid of the inner loop of the coil is not the same as the centroid of the outer loop.

For a circular coil it is clear that the dipole is constant around the coil. For a different shape, the dipole is different. However, there should be no difference in the magnetic moment, but the actual dipole generated is the same as that of a circular coil when observed from far enough away, it may not be the same when viewed from very close by. When testing the coil this should be taken into account. The board is tested by measuring the dipole instead of the magnetic torque. Which means this has to be considered.

The thickness of copper clad on a circuit board is usually given in ounces (oz). It is the weight of copper on one square foot of board. One ounce copper is 1.378mils (35um) thick. Normal PCB copper thicknesses are 1/4oz, 1/2oz, 1oz, and 2oz. Other thicknesses are possible, depending on the capabilities of the fabricator that makes the board. However, copper that is too thick creates lamination problems. A typical board would use 1/2oz (.7mil or 18um) copper on inner layers, and 1oz (1.4mil or 35um) copper on planes and outside layers.

In this case it was selected to have a 35 um copper throughout. It is to be expected that to create the inside layers there are two etched layers pressed together to make essentially 35 um copper. The thickness of the copper is essential to determine the resistance of the coil. It is calculated through eq 6.9 that the magnetic torque is exactly equal to the requirement at a voltage of 1.3 Volt. In this case N is the number of loops.

$$\bar{\mu}_{loop} = N \cdot I \cdot A \tag{6.9}$$

Unfortunately the board was designed with 35 micrometer copper thickness on all layers, but it built with 18 micrometer on the inner layers and about 30 micrometer on the outer layers. Therefore the resistance is higher than expected. The manufacture provides many different thicknesses and the 18 μm/30 um option

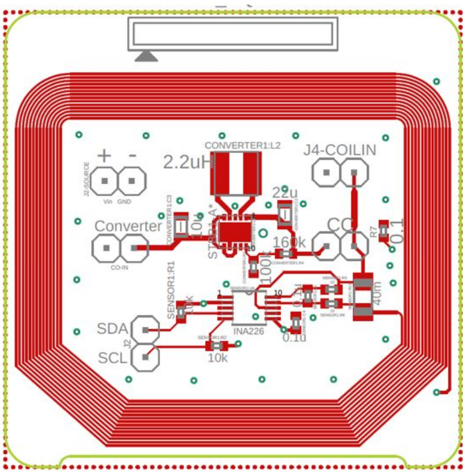

Figure 6.5: top view of the board

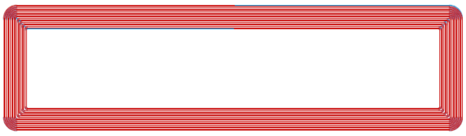

Figure 6.6: schematic of the coil in the wall (2 layers)

happened to be the cheapest at the time of order. Normally the 35/35 micrometer option is the same cost. This might be the reason the board was pooled with production run of a different thickness. Other thicknesses are much more expensive. It is recommended to make sure that 35 um/35um is chosen if another version of the board is built. Having thicker traces will improve the performance of the board.

After the PCB is created it is not yet finished. The components that go onto the board are not yet soldered. The soldering was done at the faculty of Aerospace engineering. For the prototype this took about an hour. This means that this method of constructing a magnetorquer is very efficient in terms of time spend on construction. Also, it is possible to order as many PCB's as needed. This is possible because it utilizes an existing manufacturing capability. Winding copper wire can be done mechanically as well, but then the winding apparatus must be bought. In contrast creating PCB's is very easy and cheap. Therefore this method of construction can be scaled really well, also because the cost per PCB drops the more PCB's are made, but it can also be applied to small series.

6.6.1. Construction Result

Eurocircuits always prints several copies of the PCB. In this case six PCB's passed quality control at Eurocircuits. It is always good to have spare PCB's because there is a possibility of failure at the solder stage as well. For the project one PCB was fully assembled. One turned out to be non functional after soldering the surface mounted components.

The most important part of the PCB is the integrated coil in the PCB. As a first step the resistance of the coil on all PCB's was measured. These measurements are displayed in table 6.1. It quickly became clear that the coil resistance of all coils was too high.

In order to determine why the resistances were measured more accurately by running a small current and probing the voltage at certain places in the coil. The results from that measurement are shown in table 6.2. It should be noted here that it is quite hard to accurately measure inside a via, but the sum of all measurements is equal to the voltage drop between the pads on the end of the coil and the beginning. What can be seen from the table is that the resistance of the coil on layer 2 and layer 3 is too high. These layers are the internal layers.

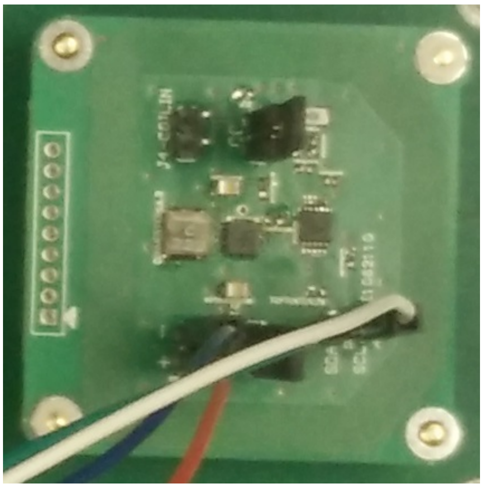

Figure 6.7: PCB coil seen from the top. the coil traces are clearly visible

It is clear that the copper foil used was a different one than intended which is why the resistance is larger. From discussion with the manufacturer it appeared that the copper thickness on the external layers is not tightly controlled, because the copper is poured at the end of the production process. This pouring is required to fill the vias. Because of the pour the copper may get thicker. That is the reason that the resistance on the outer layers is actually as expected in spite of the thin copper foil.

The trace resistance is different than designed. For the purposes of testing the board it is not terribly important. However for a flight model this oversight cannot occur. It is assumed that the fabrication was done with 18 um inner layers, 12 um outer layers. Once the board is assembled and all holes have been drilled it is copper plated to create the vias. Then the outer layers appear become 30 um due to the copper plating. This is consistent with the resistance measurements done on the board.

Because for this application it is important to control the copper thickness it is recommended that for future coils the entire coil is placed on internal layers. This has the added advantage that the board can host more surface mounted components. For this prototype it is not required to have room for more surface mounted components, but in an actual satellite board it is nice to have some extra room. Also because of the location of the loop it was impossible to use the connector on the outside of the board. Similarly it is good to have a connector to the satellite walls, because that way this board can power the coils in the walls as well. For that it is required to have a connector on the board where now there is a loop.

A second recommendation is to make sure that the PCB manufacturer knows that the copper thickness on the internal layers is important and check that the resistance is as expected upon arrival of the board.

board measurement	weight	coil resistance (measured from sensor1:R19 out to R7 in)
no:	g	ohm
1	6	22,5
2	7	21,9
3	7	22,3
4	6	22,1
5	7	22,6
6	7	22,8

Table 6.1: resistance of the PCB's, four point measurement

The properties of the embedded coils as determined by the theory and construction are shown in table 6.3.

board	layer 2 coil [Ω]	layer 3 coil [Ω]	layer 1 coil [Ω]	layer 4 coil [Ω]	sum of layers [Ω]
1	7,325	7,197	3,545	3,865	21,932
2	7,743	7,366	3,076	3,181	21,367

Table 6.2: resistance of the PCB's, measured by voltage drop, per layer.

PCB coil (as built)		3σ	
loops per layer	14		
layers	4		
resistance coil	22.3	0.3	Ω
Aggregate Area	61053		25 mm^2
Trace width	0.19		mm
Trace length	7328	5	mm
n calculated	0.061		
Wall Coil (not constructed)		3σ	
loops per layer	16		
layers	2		
resistance coil	22.4	0.3	Ω
Aggregate Area	287407	50	mm^2
Trace width	0.38		mm
Trace length	14701	10	mm
n calculated	0.287		

Table 6.3: Values for PCB coil board, and hypothetical wall coil, resistance is as measured, rest is as manufactured, uncertainty in length and area is because effect of manually changing traces to connect to via.

6.6.2. Mass

The mass of the system is quite hard to determine because most mass that is used is in the satellite anyway. There are a couple of components that would otherwise not be there on the satellite but it is also using a lot of components that are already there even if there were no ADCS system.

The ADCS PCB weighs (unpopulated) eight grams for 4 layers, and ten grams for eight layers. In addition there is the weight of the connectors connecting to the walls. Eventually because the coils are in the PCB, and all other systems also have a PCB there is very little mass penalty for adding the system. A conservative estimate would add another two grams for components and another four grams per wall for adding two additional layers and components to the walls. To save weight it is chosen to thicken only two walls and not all four.

A six layer PCB in the shape of a 3P PocketQube wall has an estimated mass of 41.5 gram. (FR4 substrate, 35 um copper, 50mm by 178 mm, 6 layers) from Euro circuits. An 8 layer PCB has a estimated mass of 44.5 gram. The mass may vary a lot based on the amount of copper remaining in each layer here it is assumed to have 75% copper remaining. There is already a six layer PCB for thermal purposes.

Total mass comes to$10+6\times2+2=24$grams

One thing to note, it is way more expensive to produce several different wall PCB's. Therefore the choice could be made to have the coil in all the walls, or three of the walls, since one wall has to be different as per PocketQube standard.

7 Measurement Setup

In order to validate the design of the torquers it is important to test them. One of the most convenient ways to test the magnetorquers is by looking at the magnetic dipole they generate. Another way is by using a torque meter. In literature one experiment is found with a torque meter. It was also found that it is easier to measure the dipole of a magnetorquer than the torque generated. [32]

It is important to place the magnetometer a certain distance away from the torquer. Lee, 2005[32] found that a good result was obtained if the magnetometer was placed about two torquer lengths away from the torquer. For the case in the paper the torquer that was measured that had a ferromagnetic core, therefore the length of the torquer is a natural reference length. That is not so for an air core as is being tested here. By bringing the magnetometers closer to the test object the field magnitude is larger, and thus the signal to noise ratio is improved.

The magnetic torquers for a PocketQube satellite may take many different shapes. It is desirable to be able to test all the torquers in the same manner. Of course the testing equipment does not have to be large enough for a CubeSat board.

In literature it was noted that when testing magnetorquers, metallic objects even a few meters away from the measurement are able to affect the measurement. [32] The magnetometer was placed in the axial direction of the magnetic field, and also in the radial direction of the field. In both cases the field was resolved accurately. It was found that when the test was performed in a field at least 5 m away from any metallic or electric equipment, the measurement was more accurate than when the measurement was performed inside a building. This shows that it is important to select a measurement location far away from any magnetic field source. [33] In addition to measuring the magnetic properties of the system it is also important to know the electrical behaviour. Use is made of a switching converter. Switching converter performance is difficult to predict theoretically, especially at low power.

The torquers have a large inductance as a result of being designed to create a magnetic field. That means that the current through the torquer is not constant over time, but the current builds up gradually when the torquer is switched on, and decreases gradually when the torquer is switched off. Therefore the response of the torquer is not instantaneous and this needs to be taken into account. The inductance also determines the minimum actuation time.

7.1. Measuring the Magnetic Moment

The effectiveness of a a magnetorquer is determined by the magnetic moment it generates. Measuring this is rather difficult. From literature it was found that the best way to measure performance of magnetic torquers is by measuring the magnetic field by using magnetometers.[32]

Magnetometers do not measure the magnetic moment of the magnet, instead they measure the magnetic field, more specifically the local magnetic field density. The is measured in (mili)gauss or (micro)Tesla. This measurement is related to the magnetic moment as in formula 7.1. This is easier to evaluate in radial form, as in equations 7.7 and 7.8. The equations relate to the magnetic field as in figure 7.1

$$\mathbf{B_r} = \nabla \times \mathbf{A} = \frac{\mu_0}{4\pi}\left(\frac{3\mathbf{r}\left(\mu_{\mathbf{loop}} \cdot \mathbf{r}\right)}{|r|^5} - \frac{\mu_{\mathbf{loop}}}{|r|^3}\right) \tag{7.1}$$

$$\mathbf{r} = \mathbf{n} \cdot |r| \tag{7.2}$$

$$\frac{\mathbf{B_r} 4\pi}{\mu_0} = \frac{3\mathbf{n}\left(\mathbf{n} \cdot \mu\right) - \mu}{|r|^3} \tag{7.3}$$

$$\mu = \begin{bmatrix} \mu_{loop_x} \\ \mu_{loop_y} \\ \mu_{loop_z} \end{bmatrix} \tag{7.4}$$

$$\begin{bmatrix} Br_x \\ Br_y \\ Br_z \end{bmatrix} \frac{4\pi|r|^3}{\mu_0} = 3\mathbf{n}\left(\mathbf{n} \cdot \mu\right) - \mu \tag{7.5}$$

$$\frac{4\pi|r|^3}{\mu_0} \cdot \begin{bmatrix} Br_x \\ Br_y \\ Br_z \end{bmatrix} = 3 \cdot \begin{bmatrix} n_x^2 - 1 & n_x n_y & n_x n_z \\ n_x n_y & n_y^2 - 1 & n_y n_z \\ n_x n_z & n_y n_z & n_z^2 - 1 \end{bmatrix} \cdot \begin{bmatrix} \mu_{loop_x} \\ \mu_{loop_y} \\ \mu_{loop_z} \end{bmatrix} \tag{7.6}$$

By placing the magnetometers in locations where θ is close to ninety degrees which means $\sin\theta$ goes to one, makes it easier to evaluate the measurement and thus reduce the solution of equation 7.8 to eq 7.10. Even if the angle theta is not zero $\sin(\theta)$ will stay close to one. In the case of the test board the angle theta is obviously not zero, as can be seen in figure 7.2, however the factor $\sin(\theta)$ is 0.97. This also reduces the effect of an error made when measuring the angle. The downside of using equation 7.10 is that is only resolves the magnitude, and the orientation of the vector has to be known in advance. This is the result of having to input the angle θ.

It was found that evaluating equation 7.6, which is derived directly from eq. 7.1 through inserting equations eq 7.2, 7.3, 7.4 and 7.5 is not possible when considering a single sensor. Also, this calculation is affected by the tilt of the sensor. When m is known the magnetic field, B is also known. However when the magnetic field is known, it may be caused by multiple possible m vectors. That is why equation 7.6 is singular, and has no unique solution. It may be possible to solve equation 7.6 using multiple sensors at once. But for now the solution is limited to solving 7.8, which has solution 7.10 This is sufficient to measure the magnitude produced by the torquers. When measuring other devices it may prove useful to further explore a solution of equation 7.6. This is especially true if the orientation of the magnetic moment vector is not known precisely.

$$B_r = 2|\mu_{loop}|\frac{\mu_0}{4\pi} \cdot \frac{\cos\theta}{R^3} \tag{7.7}$$

$$B_\theta = |\mu_{loop}|\frac{\mu_0}{4\pi} \cdot \frac{\sin\theta}{R^3} \tag{7.8}$$

$$|\mu_{loop}| = \frac{B_r \cdot R^3 \cdot 2\pi}{\mu_0 \cdot \cos\theta} \tag{7.9}$$

$$|\mu_{loop}| = \frac{B_\theta \cdot R^3 \cdot 4\pi}{\mu_0} \tag{7.10}$$

7.1.1. Sensors

The measurements are being done with a number of MLX90393 magnetometers. These are amplified hall magnetometers, created by Melexis. [34] [35]. One of the advantages of this sensor is that it can be controlled by SPI. SPI is a very simple serial communication. The advantage lies therein that several sensors can be controlled at the exact same time.

The choice for these sensors was made because they can run in SPI mode, and not just on I2C mode. These sensors are made for mobile phones. While this was common, recently more and more phones use a magnetic sensor integrated with a gyro and a gravity sensor. This sensor had a good availability, and for a mobile phone sensor a very good accuracy.

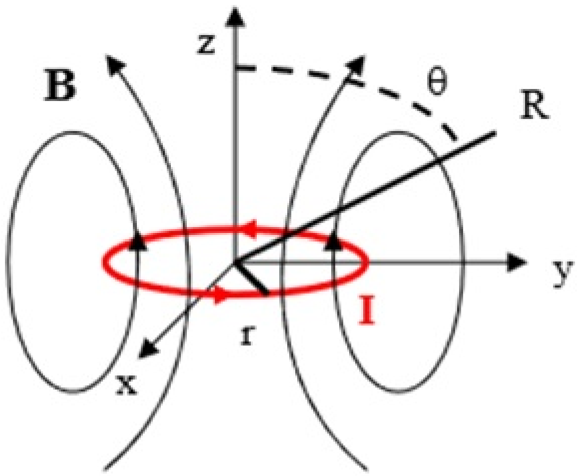

Figure 7.1: magnetic field of ampere loop *D. Acosta, 2006*

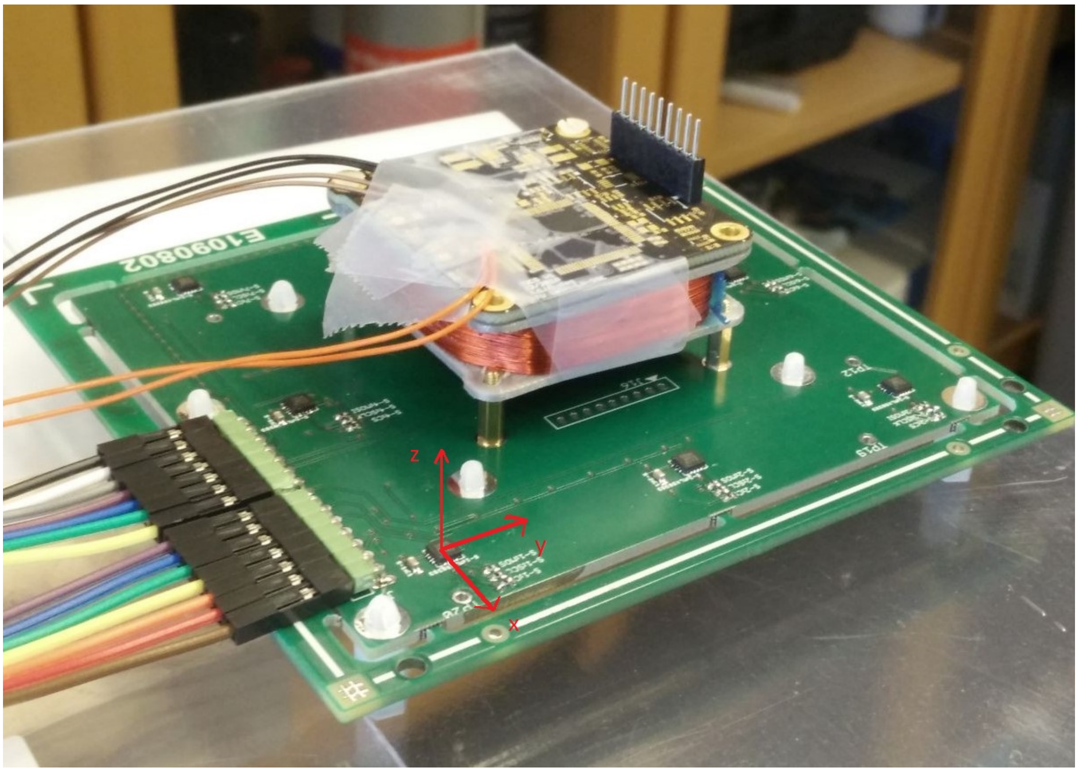

Figure 7.2: orientation of the magnetometers

7.1.2. Combination of simultaneous sensor measurements

One of the biggest challenges for this project was to obtain simultaneous measurements of several sensors. As mentioned SPI is used for this purpose. Instead of using a built in SPI module of the micro controller, digital pins are programmed to emulate SPI. In this manner up to 16 sensors can be connected at the same time. With minimal effort this can be extended to 32. An overview of the SPI connection is shown in figure 7.3. As mentioned most magnetic sensors designed for mobile phones communicate via I2C. MLX90393 magnetometers can also communicate via I2C. However, the sensor only has 4 native addresses so if more are needed, multiple masters or a different solution must be used. Even so, the I2C buses are more difficult to synchronize so there may be a delay in sensor readout.

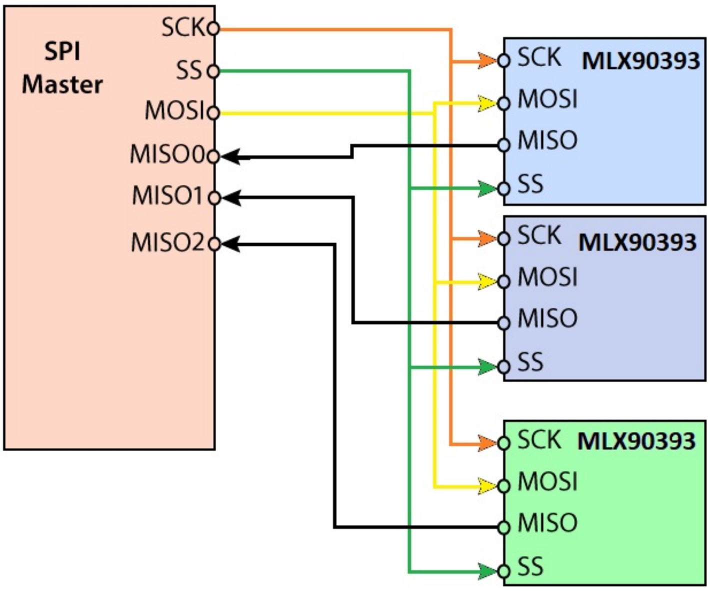

Figure 7.3: SPI layout

This is solved by using SPI communication. By duplicating the master signal the sensors all receive the same instructions at the same time. One of the drawbacks is that there can be no mistakes in the communication because there is no fallback. If one of the sensors does not receive a bit correctly then there is a chance that it will not respond correctly. The sensor will return with a status byte which contains an error bit. Should it be set, or should not all status bytes for all sensors read the same, then a communication error may be discovered.

In order to be able to control the sensors in this way a control code was written especially for this thesis work. The code is written for a Texas Instruments MSP432P401R (LaunchPad). It was considered to install that micro controller on the measurement board however, that has the drawback of having an active device possibly interfering with the measurements as well as having to expend extra effort and money to make sure the microcontroller works properly, and TI-launchpads can be bought relatively cheaply.

The code is written in such a way that it takes advantage of the higher level functions of the Energia platform. Energia is based on Arduino, but modified to operate a Ti-launchpad. The reason for choosing a TI-launchpad is that a general Arduino board is not powerful enough for this application. As mentioned the code is designed to work up to 16 sensors. However the Energia functions used are somewhat slower than more direct port commands. When adding more sensors the clock speed of the communication has to go down. There is no actual limitation of the clock speed but the more sensors are added the less measurements can be taken, unless the switch is made to port commands. Port commands are more time consuming to program.

In literature it is mentioned that a good distance is twice the actuator length. Unfortunately that translates poorly to the current setup. Instead of measuring actuators with ferromagnetic cores, the setup is mostly used to coils with a large area but almost no length. The spools with a finite length, the wire wound spools, have a length of 10.7 mm. Sensors would have to be placed 21.4 mm away from these spools.

Putting the sensors further away from the coil will decrease the strength of the magnetic field. On the other hand moving the sensors closer to the coil will make the sensor more sensitive to the shape of the magnetic field. It is unlikely that the magnetic field generated is perfectly spherical.

Because the test setup is used to measure the magnetic field of various different coils it is also impossible to make sure distance to the sensor is the same for every coil. By using multiple sensors around the coil the effect of the shape is minimized. On the other hand the length of the coil used in literature is much longer than the length of the coil used here. It is unclear that there is an optimal sensor placement distance. For practical reasons it was chosen to put 9 sensors on a square grid, with each sensor 35 mm apart. This will result in distances between sensor and coil between 5 and 40 mm.

7.1.3. Test Board

In order to mount a large number of sensors a test board is developed on which the sensor grid is placed. As is mentioned the measurement location should be mostly free of magnetic fields created by electronic equipment. The measurement equipment itself is also electronic equipment. This was the reason to design the measurement board such that the only active components on the board are the magnetometers. The microcontroller is placed some way away from the sensors, connected by a cable. All wires will be bundled because that is easier in practice. This means that for example clock and data lines will run parallel. This will cause interference and the data lines may pick up the clock signal and vice-versa. Given the low clock-speed signal interference should not really be a problem.

The capacitors do generate a magnetic field but in theory this field should be zero outside the capacitor. The PCB itself also could cause a magnetic field due to possible magnetic materials used. The magnetometers should use very little power, therefore the currents in the board will be very low. Also the area of the current loop is kept as small as possible by using parallel power and ground planes. This way currents should balance and do not traverse large loops. Due to the intersecting signal lines the current paths are not completely parallel and some magnetic field may occur. In order to reduce this issue several additional traces were made to make sure all parts of the PCB are connected in such a way that the current does not have to travel around the edges of the PCB to reach all sensors.
The test board is a PCB manufactured in the same why as the PCB coil. In contrast to the PCB coil the PCB is much larger though. The faculty of Aerospace Engineering has recently acquired a pick and place machine and a reflow oven. The test board had the honor to be the first PCB which had its surface mounted components assembled with these new machines.

The pick and place machine uses a pneumatic suction system to pick up surface mounted components. The machine is manually operated by a a person and allows for faster and better assembly of PCB's. There is also a way to automate the machine but that is intended for long production runs, not for a single of small batch of PCB's.

The process of mounting the surface mounted components onto the PCB follows three steps. First, using a stencil for the PCB which is also ordered from the manufacturer of the PCB, solder paste is applied to the PCB. Using this method means that on each pad of the PCB there is an even amount of solder. This is important because that means the sensors will be level with the PCB. If solder is unevenly distributed, one side of a sensor maybe higher above the PCB compared to another side. The stencil is removed and using the pick and place machine, the the surface mounted components are placed on the PCB. The advantage of this is that due to the magnifying camera system and the vertical motion of the machine the sensors and other components are placed accurately on the pads and level on the PCB.

The final step of the process is the reflow oven. In the reflow oven the solderpaste melts and the components are soldered to the board. The temperature profile of the oven is very important. Because of surface tension and the tendency of the solderpaste to adhere to the pads and not the soldermask of the PCB, all the components are pulled into perfect position over the pads. Using this method of mounting the sensors therefore makes sure that all sensors are neatly placed and level on the PCB which improves the accuracy of the measurement.

7.1.4. Calibration

It is important to calibrate all sensors. This is because of several reasons. First of all, not all sensors have the exact same orientation. This is because of inaccuracies in sensor installation.

Due to the static nature of the problem the calibration is less of an issue than the calibration for a flight magnetometer would be. If the magnetometer is used in flight it is critical to calibrate many things. Because of the static nature, of the magnetometer board many effects can be calibrated out in the same manner. The most important thing to calibrate out is the hard iron effects. Fortunately this is also the easiest to calibrate. Another thing that is important is the temperature. In order to minimize the tilt effect it is important to take into account all three axis of the sensor when evaluating a measurement. It is necessary to evaluate the change in the entire vector reading.

The calibration method chosen was to zero all measurements. This takes care of all hard iron and location effects, except transient ones. By reading out all axis of all the sensors also the effect of possible tilt is reduced. The way this is achieved is by reading measurement data for a while. The mean of that data is calculated and then subtracted from all measurements. The measurements will then have a zero mean. Subsequently the experiment is started, and what is measured is the difference from the base state while the experiment is running. It is therefore important not to change the environment during the experiment because that influences the measurements. If the environment is changed the calibration has to be repeated.

7.2. Power Measurement

The power is measured at the power supply and at the entrance of the coil. The power supply is set at 3.3 volt. If the switching converter is used, the voltage and current are measured again after the converter. This then shows the efficiency of the switching converter and the efficiency of the coil.

In order to measure the power supply current a four point measurement is used. This is done with a AGILENT desktop multimeter.

The current at the output of the switching converter is measured by a chip called INA226. This chip is integrated on the PCB with the switching converter. This chip uses a specified resistor. of 0.04 Ohm. The voltage is measured at both sides to invert the current. [36]

At the power supply the current is measured. Initially it was assumed this could be done with a desktop multimeter set to A/C current measurement. The way this is measured can be described by the figure 7.4 The

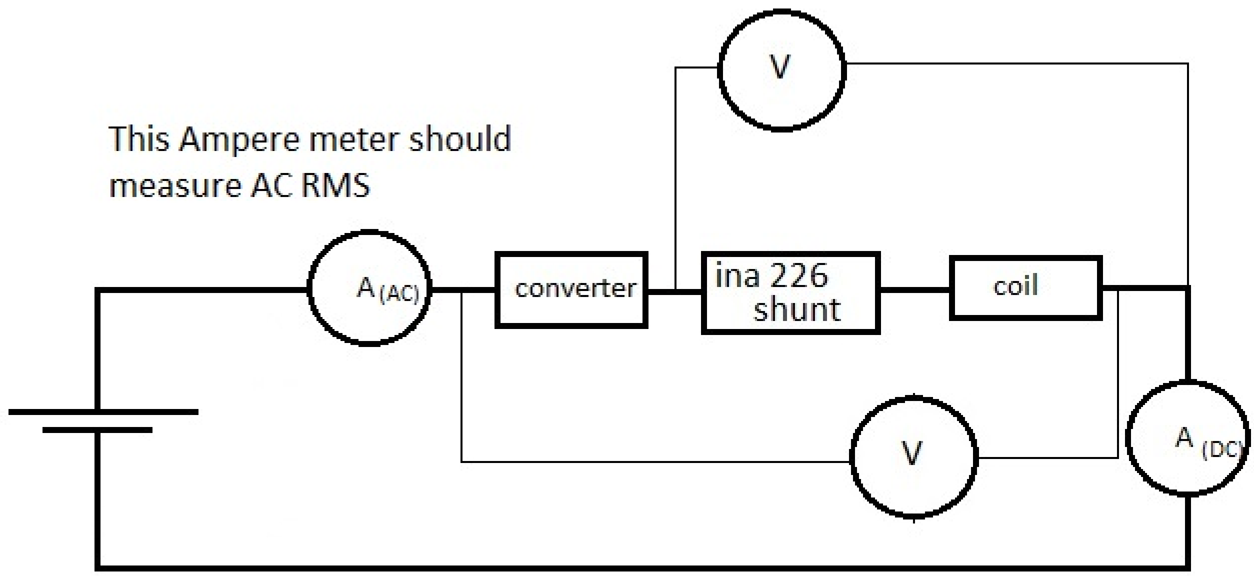

Figure 7.4: circuit schematic showing location of measurements

INA226 sensor measures the voltage difference across the shunt. Since the resistance of the shunt is known quite accurately, the current can then be calculated. Measuring the power and current gives an answer to the efficiency question. It was found during trials that the current measured by the multimeter was not accurate. This is due to the nature the current that is switched on and off. Therefore a current probe was used, connected to the oscilloscope. Using that setup the current was measured.

The current exiting the coil is more like a DC current. Therefore the multi meter was used to measure the DC current after the coil.

7.3. Determination of switching time

Using a multi-line oscilloscope the switching time of the coil can be found. This is important because due to the large impedance of the coil it takes some time for the current to reach a constant value. The reason is that impedance a time sensitive parameter.

When the coil is embedded in the control system this switching time will influence the control time. Especially for the stronger coils this can make a large difference.

7.4. Measurement Accuracy and Precision

In order to determine how well the actuator performs one of the issues is the measurement accuracy and precision. Precision is the variance the the measurements, whereas accuracy is a measure of how close the measurement result reflects reality. Measurement accuracy and precision depends on a lot of different factors, the most important factors are listed below.

- correct translation of magnetic field strength to magnetic moment
- correct translation of sensor output to magnetic field strength
- Environment noise such as magnetic fields created by equipment
- physical accuracy of sensor location
- Sensitivity of the sensors
- Calibration of the sensors
- Noise in the electronic readout circuit
- Noise filter, how successfully the noise can be filtered

The MLX90393 sensor allows the user to select the sensitivity by choosing the gain of the sensor. List of possible settings can be seen in appendix C or the data sheet [34]. The sensitivity chosen is the best possible sensitivity, with max gain and zero res resulting in a sensitivity of 0.1502 mg/LSB. In order to check this there is also a test done with a high current single circular loop.

There is a difference between the x and z axis sensitivity. With the same gain the sensitivity in the z axis is 0.242 mg/LSB. The sensor sensitivity in the y-axis is the same as in the x-axis. Given the sensitivity the output of the sensors can be scaled. However there is also noise in the sensor, which decreases the measurement precision. Each current carrying wire has its own magnetic field. This influences the measurement because there are current carrying wires nearby.

The MLX90393 sensor can change the measurement noise by choosing the conversion time. The user can select the noise level by choosing adapting a digital filter on the sensor. In it is possible to over-sample and this will improve the measurement as well. One peculiarity of the sensor is that the factory setting of the sensor gives massive noise, and makes the sensor unusable. Once this was discovered, the sensors were programmed to optimize noise reduction. In the end a setting with a conversion time of 33 ms per axis was chosen to which has good noise performance as can be seen in figure 7.5. A similar figure for the z-axis is in appendix C Also due to the noisiness of the measurements it was decided to introduce a fast acting Kalman filter to the measurement. By using this filter the noise is further reduced. In order to have adequate response to changes in the magnetic field, the Kalman filter has to allow for a reasonably large process noise.

In addition to sensor noise there is environment noise. This can be seen in figure 7.6 where suddenly a large spike in the measurement occurs when the elevator starts moving. Also there is noise caused by other lab

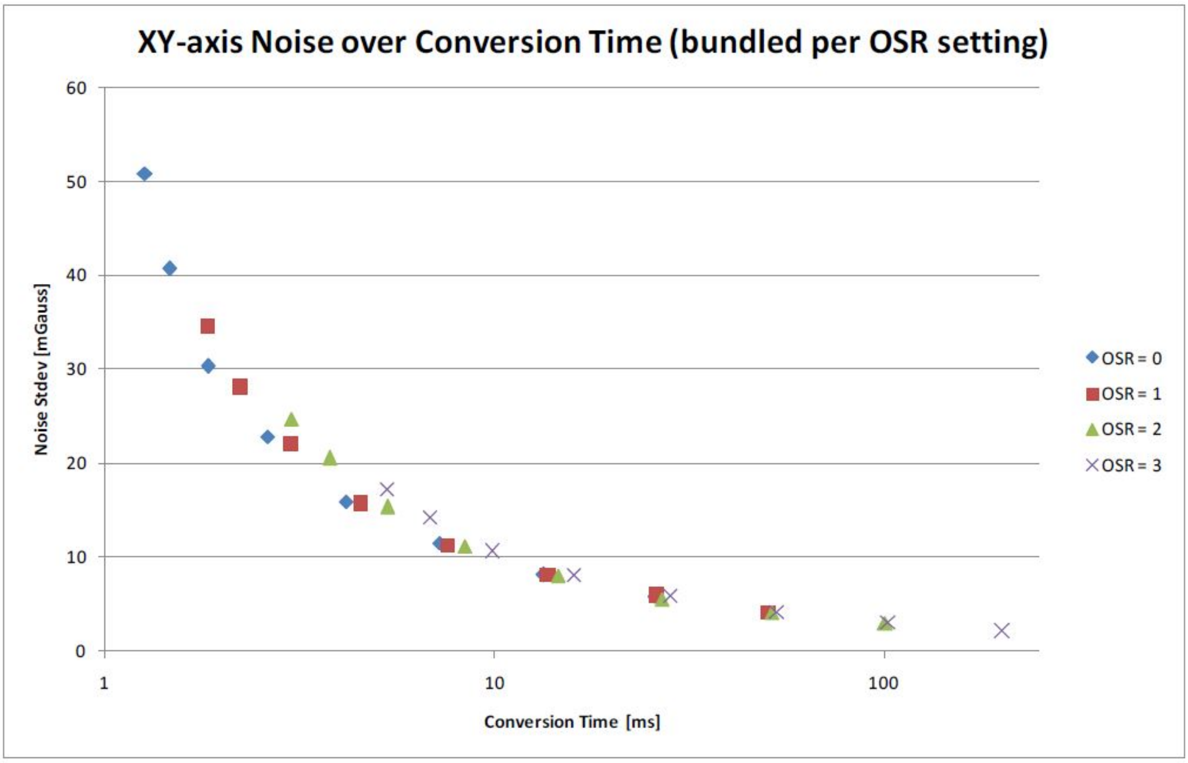

Figure 7.5: Noise of MLX90393 as function of conversion time [37]

equipment, the lighting and so on. Also moving some equipment in the lab caused the calibration to fail, which is shown at the end. In order to deal with these effects a time period is chosen for where there are no sudden spikes. And care is taken not to move anything while measuring.

For comparison figure 7.7 shows a measurement done outside in a green field. One thing thing that stands out is that in the lab the temperature is very constant and outside the temperature varies. If the temperature of the sensor increase the magnetic readout also changes. The increase in temperature was mainly caused by the sun. When shade was provided for the setup the temperature was fairly constant, but in this case much higher than in the lab because it was hot day.

The sensor has a standard deviation of about 3 mGauss per measurement, as given by figure 7.5. All sensors are set to use OSR 2 with a 100 ms conversion time. (33 ms per axis). The graph is plotted for every axis. It is impossible to have a 100 ms conversion time for a single axis with any sensor setting. By using a Kalman filter, the sensor measurements are averaged over time. Also a lot of time averaging is done already at the sensor level, making the conversion time longer. In figure 7.5 the first mark for each OSR level is not averaged, the subsequent marks are using a averaging filter to decrease noise but increases conversion time.

In spite of the time averaging the resulting measurements still exhibit a lot of noise. This noise stems from a few possible sources.

- sensor noise that is not filtered or averaged out
- changes in the environmental magnetic field
- currents on the sensor board close to the sensors
- small variations in the current in the coil

Since all sensors are read out at the exact same time, if is the environment or the coil itself causing all the noise that noise should be correlated between all sensors. In order to investigate the correlation a few plots

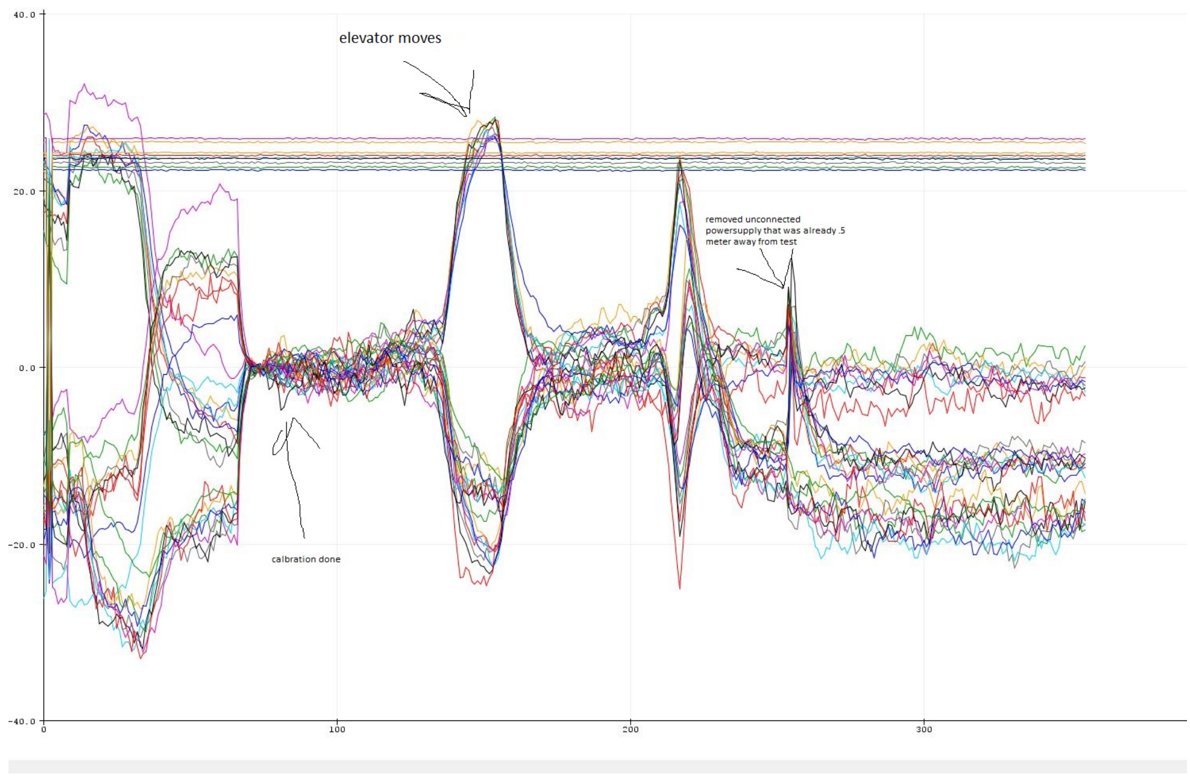

Figure 7.6: Building noise

were made, see figures 7.8 where the correlation of all sensors to sensor Y 1 is plotted, figure 7.9 where random correlation between the sensors is plotted, and 7.10 which shows the absolute deviation from its mean for each sensor. Since it seems there is no pattern in the plots the assumption is made that the noise has a low correlation between the different sensors. The plots were created by using the absolute deviation from the mean for one sensor and plotting it as a function of the absolute deviation from the mean for another. Based on that each sensor is regarded as a random variable with a true signal and noise. The noise is likely a combination of all four possible sources.

If all sensors would be uncorrelated the variance could be reduced. It cannot be maintained that the variance in sensors outputs are uncorrelated, however, correlation is low. The effect of the environment should be similar for all sensors. This can be seen in figures, 7.8 and 7.9.In figure 7.8 every other sensor is plotted as a function of the first sensor, in figure 7.9 several sensor pairs are compared. In both cases there appears to be very little correlation. From this plot 7.11or this one 7.12, the variance is calculated for the sensor for the area between the short vertical lines, using the equation 7.11. Therefore for each sensor axis a variance is obtained. By taking the root of the variance and multiplying with three the 3σ is obtained. This is then plugged into the equation for getting the magnetic moment 7.10. The precision drops with distance because the deviation is multiplied by the distance cubed, hence for sensor with the same variance in the measurement the precision improves if the sensor is very close to the torquer.

$$s^2 = \frac{\Sigma\,(x_i - \bar{x})^2}{n-1} \tag{7.11}$$

- n = number of samples
- s^2 = variance
- x_i = data point
- $\bar{x}$ = mean

That means that combining the results from all applicable sensors gives a better accuracy than just depending on a single sensor. Unfortunately the difference between sensors is large which makes it hard to propagate

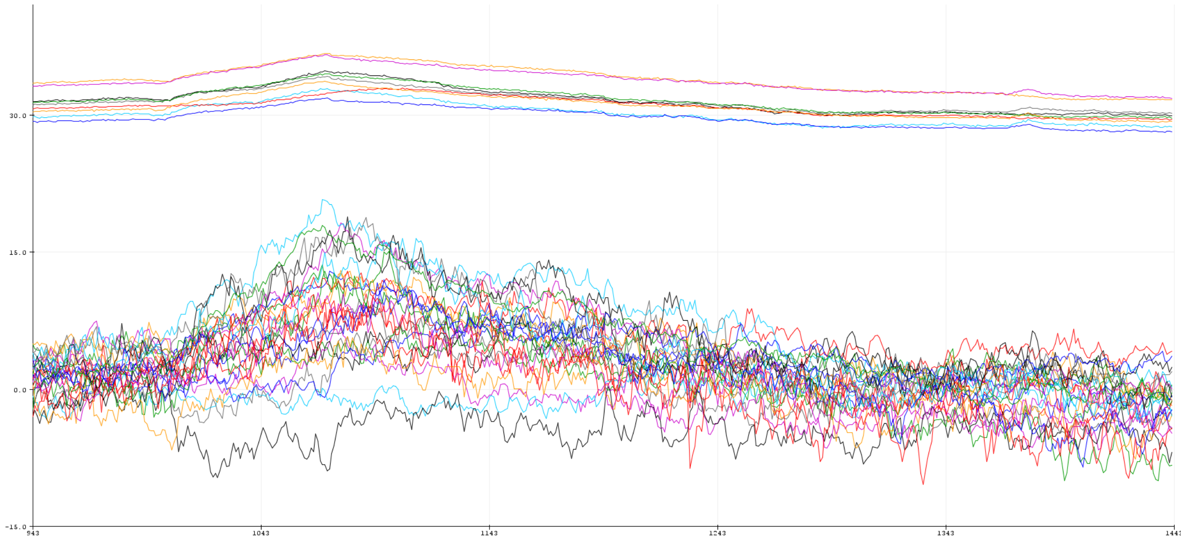

Figure 7.7: A green field measurement, the effect of sun and clouds on the sensors is visible. The lines at the top are the temperatures of the sensor as indicated by the internal temperature of the MLX90393

the uncertainty. (see chapter 8 for more test results) One explanation could be that the magnetic field is not the same at each sensor location due to the shape of the coil. Another explanation is that the sensors have differences in output even though they are supposed to be the same. This could be possible because these sensors are mass produced for use in mobile phones or tablets to help determine orientation of the device and are not really scientific instruments. By using many sensors as in this case taking the average of all sensors should mitigate this.

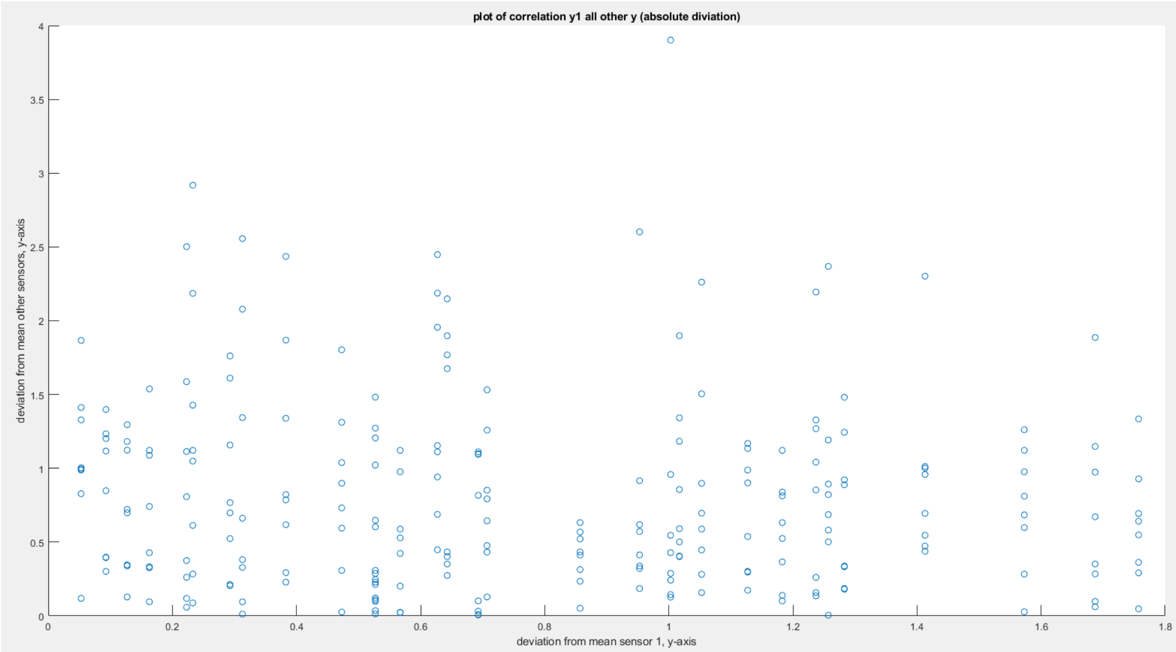

Figure 7.8: Correlation between sensors

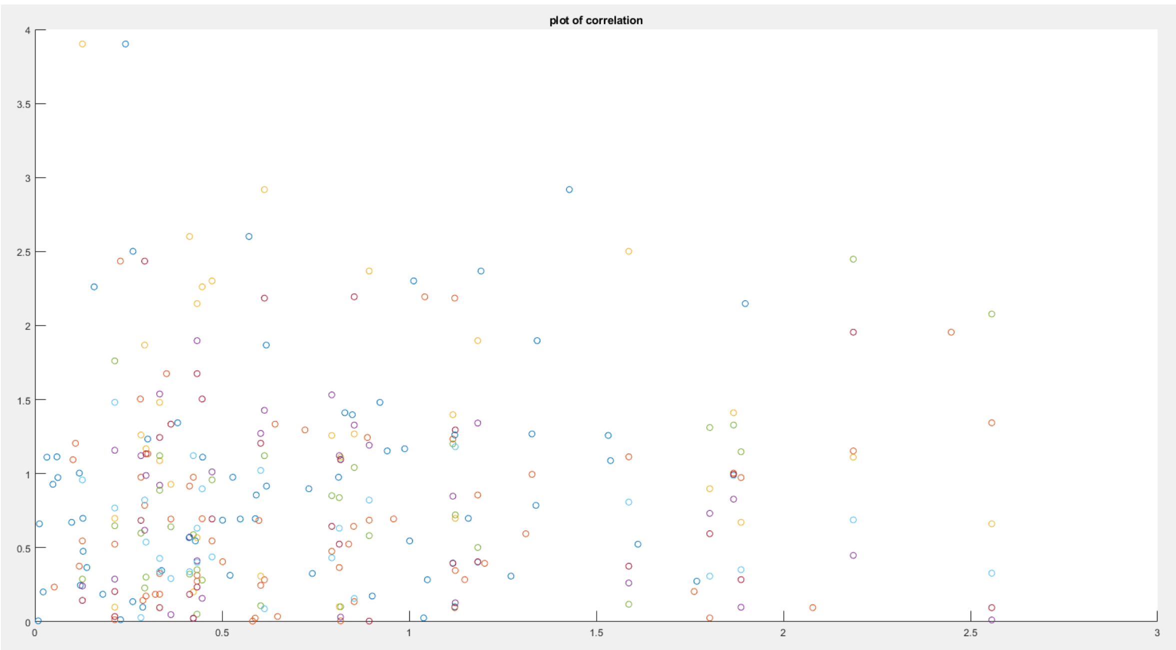

Figure 7.9: Correlation between sensors

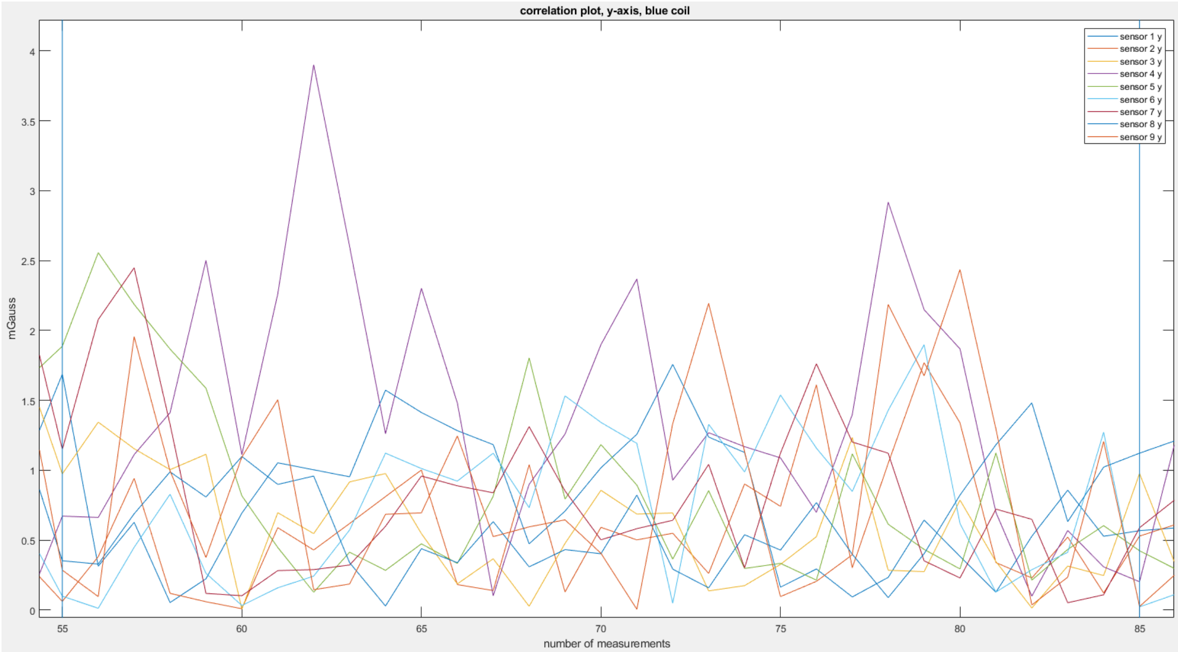

Figure 7.10: Correlation between sensors

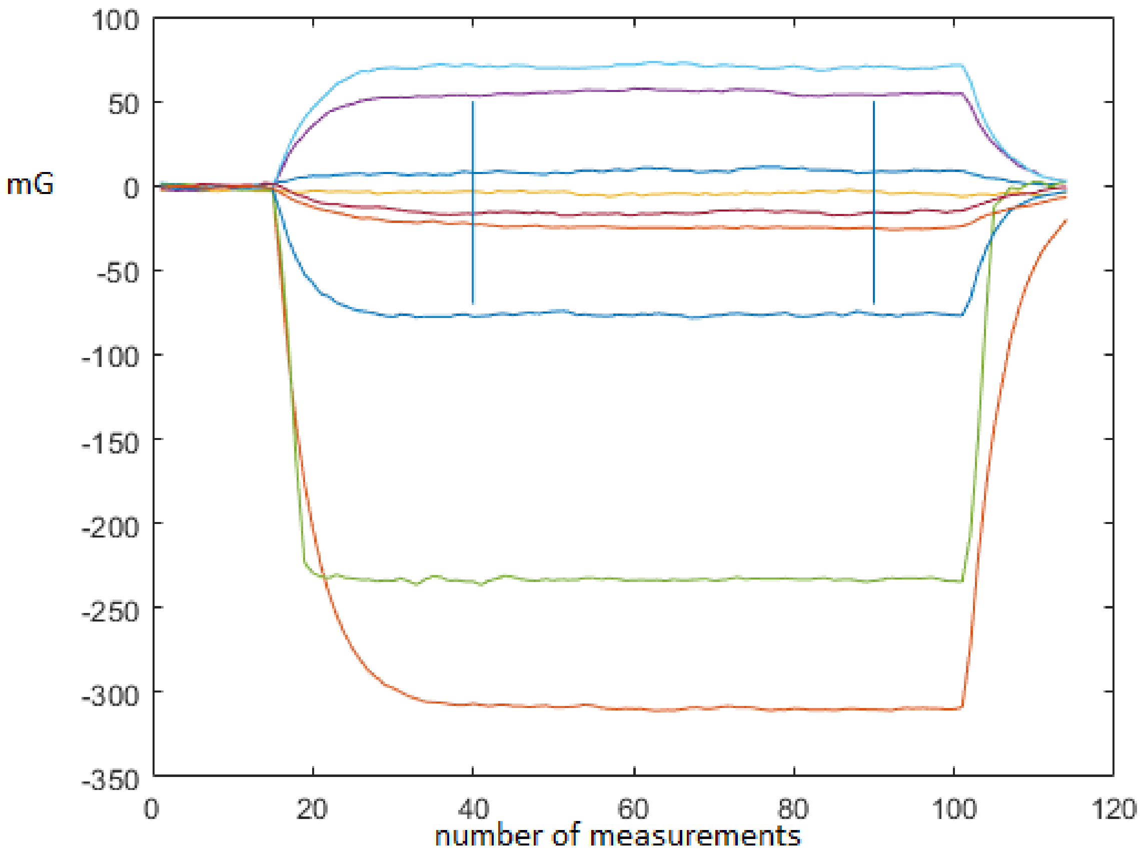

Figure 7.11: Example of a Measurement, the measurement is taken between the two vertical lines, the vertical lines only delimit horizontally.

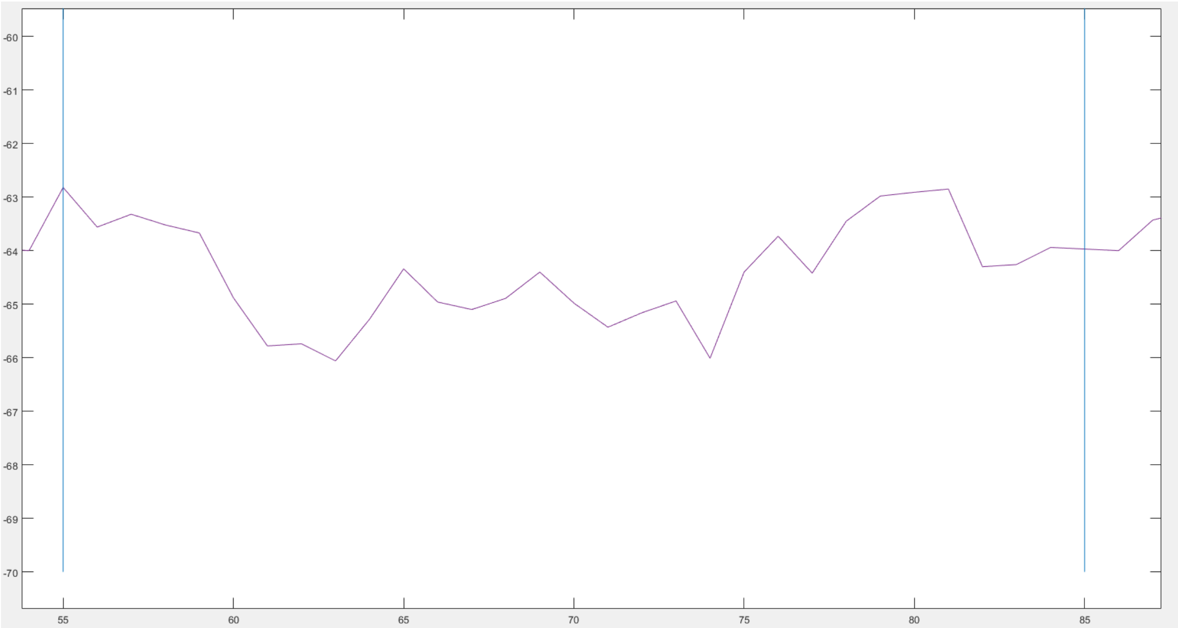

Figure 7.12: Sensor 4 Y axis

Accuracy of the magnetic measurement is not completely known. One of the reasons is that the distance between a sensor and the test item increases the accuracy but reduces the precision of the measurements. This is because the conversion formula in equation 7.8 assumes a small area of the torquer, meaning, the area is small compared to the distance to the magnetometer. Due to the size of the coils this is not really true however.

This was found when measuring the response to a coil with a large current as in figure 7.13. The diameter of the coil is 128.21 mm and the current 4.893 A. The center to center distance is 114.26 mm. The accuracy issue can be seen in this setup. For this reason the magnetic moment may be overestimated by sensors close to a magnetorquer.

The conversion from sensor readout to mGauss is done in the micro-controller. The sensor outputs in bits. The conversion rate is taken from the data sheet for the sensor. While this appears to be very accurate, it is very difficult to test the conversion rate. Therefore in an attempt to do so the setup of 7.13 was used. The idea was that with the single coil it would be easier to calculate the magnetic dipole.

However, this proved to be wrong because of the radius of the coil. The coil radius is so large that the sensor is not seeing a dipole but a large wire current. Therefore to validate the response and thus scaling of each sensor a better way to induce a known local magnetic field needs to be developed.

The radius of the magnetorquers is much smaller than the radius of the coil in figure 7.13, reducing the accuracy issue but not eliminating it. The sensor outputs are given in 7.14. At first this looks as expected, however the sensor closest to the thick red wire showed a magnetic field much larger as would have been expected from a dipole centered in the middle of the Petri dish. The magnetic field in the sensor location is given by the Biot-Savart law. This could be used in the future to examine this problem further.
The goal is to find a constant value for the magnetic moment that is as close as possible to all the output from all sensors. In order to do this a weighted mean should be calculated where the weights are dependent on the confidence in each measurement. The variance in each measurement is uncorrelated to the variance in the other measurements. If all measurements are within the 3 σ range of all other measurements, they are compatible and can be combined into a single value with a combined variance. In general this is not the case for the measurements from the test board therefore, a simple average is taken for all the sensors and the variance of this value is determined with formula 7.11

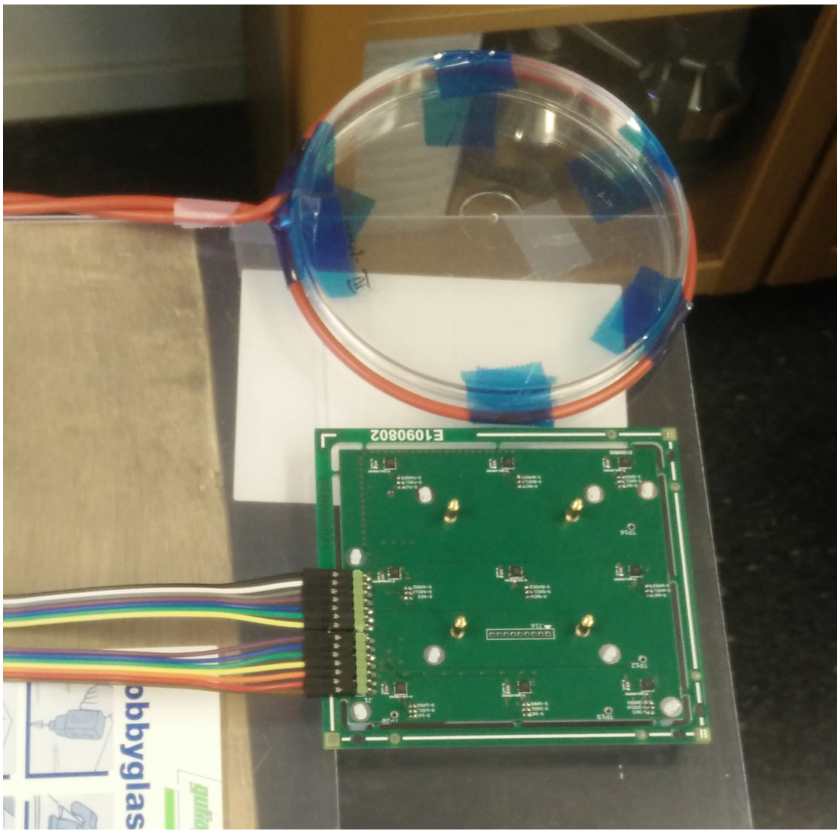

Figure 7.13: Test setup with a large coil

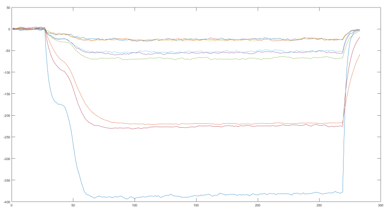

Figure 7.14: This is a plot from the z-axis data for the setup in figure 7.13

The accuracy of the measurement is impacted by the temperature, by possible slope biases in the sensors and deviations of the slope as specified by the datasheet. Moreover it is impacted by the limitations of the inverse formula for determining the magnetic moment from a magnetic dipole. This is also assuming that the current in the coil is measured accurately, but there are less reasons to assume this is the case. Nevertheless it depends on the function of the multimeter used and the accuracy of the resistance in the INA226. For the current measurement it is justified to assume a accuracy of better than 1%, based on manufacturer data.

The multimeter is expected to have an error of less than 55 μA with a current of 100 mA [38], which is an error of 0.055%. The case for INA226 is less good which has a 040 miliOhm reference resistor with an accuracy of 1%. The sensor itself has a 0.1% gain error, and a 10 μV offset. During the test a voltage was observed across the reference resistor of 2972 μV. Therefore the current sensor has a measurement accuracy of about 1.5% [36].
In addition to that, when a wire coil was active for a while it was observed a very slight decrease in current, a few tenths of a milliAmpère. It is assumed that this is caused by the effect of electrical heating on the resistance of the wire. This should impact the magnetic field but was not clearly seen in the magnetic field measurement.

8 Results and Discussion

The most important tests are meant to discover the factor N which determines the coil torque. The controller can then use this information to determine the current in the coil and thus the torque on the satellite.

In addition to this the electrical properties of the system were tested. This is important because these also determine the power efficiency of the system, and this can determine the minimum actuation time. Because there are several inductive elements in the system the current will not flow instantly as in a resistor but will grow over time. This is unavoidable because the objective is to generate a magnetic field. In order do generate a magnetic field a inductor is required.

8.1. Performance of the Switching Converter

The efficiency of the switching converter was measured while it was delivering an output of 1617 mV at an input of 3210 mV. The switching converter as powering the PCB coil. The measurement was done while the coil was continuously powered. The measurement was executed as described in section 7.2 it was expected to have an efficiency slightly larger than 80%. This was the efficiency calculated during the design of the PCB coil magnetorquer. Unfortunately it has turned out that the efficiency is about 65%.

Table 8.1: results switching converter

Device	continuous on	value	unit
INA226	Current:	73.5	mA
	Voltage:	1617	mV
	Power:	118	mW
current probe	current square wave RMS	56.5	mA
TENMA 72-7770	Voltage	3210	mV
	power	181.365	mW
Agilent 34401A	current DC exit	60.4	mA
TENMA 72-7770	Voltage	3210	mV
	power	193.884	mW
INA226 consumption	current	330	uA
	voltage	3210	mV
	power	1.0593	mW
DC exit current	efficiency	0.61 +-0.05	
current probe	efficiency	0.65 +-0.05	

8.2. Induction Test

In figure 8.1 the smallest pulse width that gave a usable actuation is displayed. shorter pulses give irregular peaks. Blue is coil current(voltage), Yellow is supply voltage. Yellow scale is 1 V, blue scale is 0.5 V. A more usefully actuation time is shown in 8.2, where the actuation is switched at a rate of about 40 Hz. Important is to note that the switch is between the power supply and the switching converter. It could also be possible to have the switch behind the converter. That way the convert would not have to turn itself on first before regulation starts. That may reduce some of the peaks at the beginning.

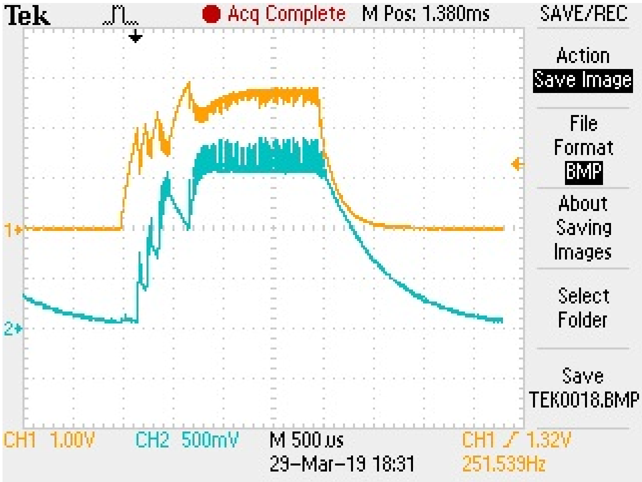

Figure 8.1: minimum actuation time 2 milliseconds

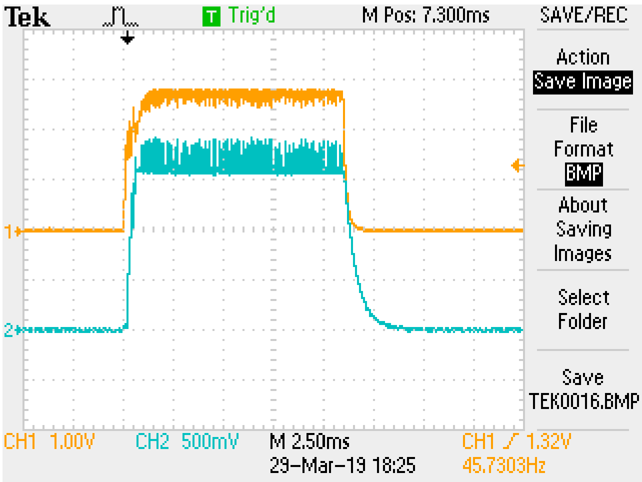

Figure 8.2: average actuation time

8.3. Magnetic Moment Measurements

The tables in this section show the results of the magnetic tests. Not all sensors are used in each case because the method of calculation requires θ to be small, see equation 7.10. Because $\sin(\theta)$ is has significant deviation from one, equation 7.8 is used to calculate the magnetic moment. For example sensor 5 has been removed from table 8.2.

The variance is calculated for each sensor, because a range of measurements is available for each sensor. This variance is given in the column following each sensor measurement. All the sensor measurements are given in $[Am^2]$, including the deviation. The deviation is given in 3σ or three times the standard variation. Based on the variation in the measurements it is not useful to combine standard deviations of each measure-

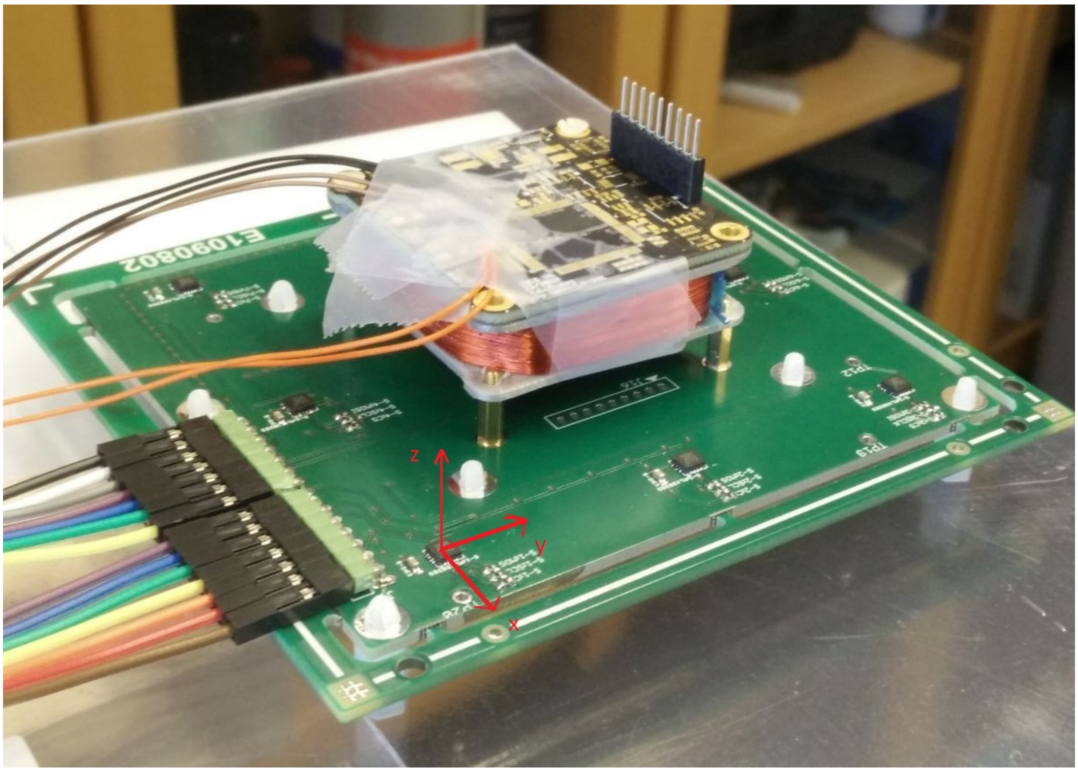

Figure 8.3: Coils mounted on the test board

Table 8.2: result from applying eq 7.8 for each sensor in the test setup in figure 8.3, for red coil, 1V6 to 2.2V. All sensor measurements are calculated back to $[Am^2]$, the final two columns are for a different setup, see figure 8.4

Voltage[V]	1.6	3σ	1.8	3σ	2	3σ	2.2	3σ	1733 mV	3σ
current [MA]	41.56	0.07	45.85	0.08	51.56	0.09	55.34	0.09	50.07	0.08
sensor 1	0.0140	0.0018	0.0169	0.0014	0.0187	0.0008	0.0186	0.0008	0.0109	0.0008
sensor 2	0.0205	0.0007	0.0231	0.0005	0.0259	0.0004	0.0272	0.0005	0.0092	0.0005
sensor 3	0.0133	0.0018	0.0157	0.0010	0.0179	0.0009	0.0176	0.0007	0.0114	0.0007
sensor 4	0.0194	0.0007	0.0221	0.0004	0.0248	0.0003	0.0258	0.0002	0.0123	0.0002
sensor 6	0.0175	0.0008	0.0198	0.0005	0.0222	0.0005	0.0235	0.0004	0.0088	0.0004
sensor 7	0.0138	0.0007	0.0168	0.0005	0.0183	0.0003	0.0182	0.0002	0.0148	0.0002
sensor 8	0.0205	0.0006	0.0231	0.0004	0.0257	0.0002	0.0273	0.0003	0.0130	0.0003
sensor 9	0.0133	0.0022	0.0158	0.0020	0.0177	0.0013	0.0178	0.0009	0.0197	0.0009
mean	0.0165	0.00986	0.0192	0.00971	0.0214	0.01104	0.0220	0.01317	0.0125	0.0105
n measured	0.3979	0.23719	0.4177	0.21186	0.4147	0.21418	0.3978	0.23802	0.2497	0.20961
n calculated	0.2870		0.2870		0.2870		0.2870		0.2870	
difference	1.4		1.5		1.4		1.4		0.9	

ment. The standard deviation of the mean shown in the table is therefore calculated from the variation in sensor results.

Table 8.2 has an additional column which shows a different measurement of the same coil. This result is separated by a double line. In this case the coil was not placed on the board as in figure 8.3, but instead placed off to the side of the board a a distance of about 111.1 mm, at the same level as the test board, closest to sensor 2. This was done to validate the results, because the measurement could be affected by the proximity of the sensor to the coil, similar to the result of the test shown in figure 7.13

As can be seen in tables 8.2, 8.3, and 8.4, all have slightly higher measurement results than expected. The factor n was calculated based on the construction of the magnetorquers in chapters 5 and 6. This is shown

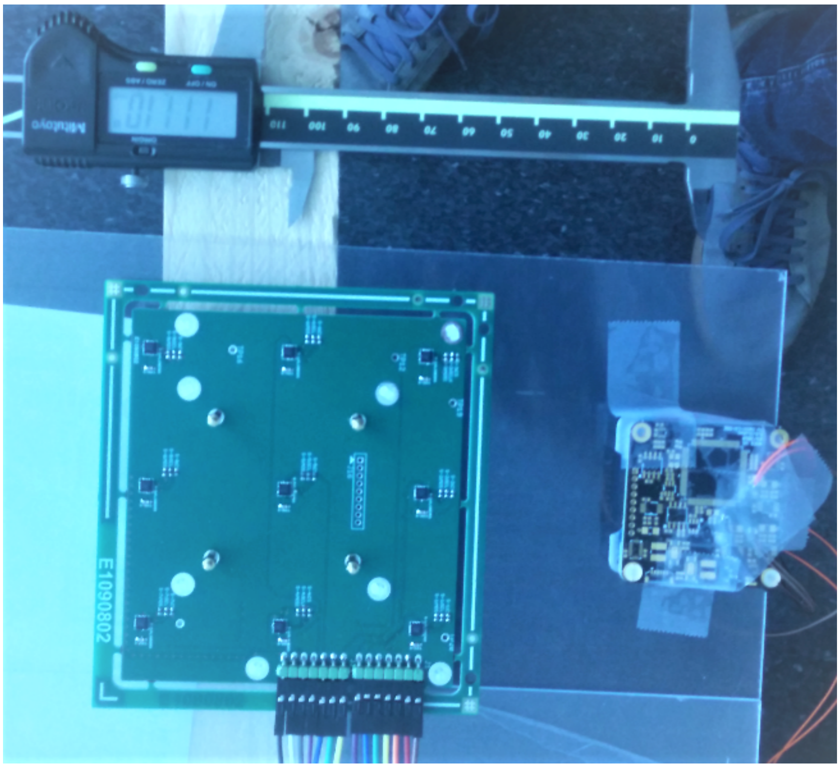

Figure 8.4: Coil placed some distance away from test board

Table 8.3: result from applying eq 7.8 for each sensor, for blue coil, 1V6 to 2.2V $[Am^2]$

Voltage[V]	1.6	3σ	1.8	3σ	2	3σ	2.2	3σ	$\sin(\theta)$
current[mA]	52.93		58.82		65.34		71.51		
sensor 1	0.0042	0.0003	0.0047	0.0003	0.0052	0.0003	0.0059	0.0002	0.8291
sensor 3	0.0043	0.0002	0.0049	0.0002	0.0058	0.0002	0.0061	0.0002	0.8160
sensor 4	0.0048	0.0003	0.0053	0.0001	0.0061	0.0003	0.0067	0.0003	0.9660
sensor 6	0.0046	0.0002	0.0051	0.0001	0.0057	0.0001	0.0063	0.0001	0.9558
sensor 7	0.0046	0.0010	0.0054	0.0010	0.0060	0.0009	0.0068	0.0008	0.6555
sensor 9	0.0042	0.0013	0.0048	0.0009	0.0055	0.0009	0.0058	0.0009	0.6027
mean	0.0045	0.0007	0.0050	0.0009	0.0057	0.0011	0.0063	0.0012	
n	0.0842	0.0139	0.0841		0.0865		0.0884		
n calculated	0.0643		0.0643		0.0643		0.0643		
difference	1.3092		1.3087		1.3462		1.3749		

in the tables in the row starting with "n calculated". The row above that, n, shows the factor n determined from the measurement results. The factor n is the link between the magnetic moment of the coil and the current running through the coil as in equation 8.1. This is important information for the control software of the satellite, which can measure the current much more easily than the magnetic moment.

$$\mu = n \cdot I \tag{8.1}$$

It is likely that the size of the coils and the proximity of the sensors mean that the sensor see the current flowing through the wires of the coils rather than the resulting dipole. In a future version of the test the location of the sensors and the coils should be chosen to account for that, or, the magnetic field should be modeled more extensively, such that the magnetic field can be better related to the magnetic moment. In table 8.2 the last column shows a result that is very close to the expected result. In that column there is a measurement done from further away. The fact that this measurement does seem to have a more accurate result is is an argument for this explanation.

Table 8.4: result from applying eq 7.10 for each sensor, for green coil, 1V6 to 2.2V $[Am^2]$

Voltage	1.6	3σ	1.8	3σ	2	3σ	2.2	3σ	$\sin(\theta)$
current [mA]	48.17	0.08	55.20	0.09	61.09	0.10	71.51	0.12	
sensor 1	0.0045	0.0006	0.0052	0.0013	0.0059	0.0007	0.0067	0.0009	0.7424
sensor 2	0.0045	0.0002	0.0053	0.0003	0.0058	0.0003	0.0062	0.0003	0.9930
sensor 4	0.0048	0.0004	0.0056	0.0005	0.0058	0.0006	0.0063	0.0004	0.3371
sensor 5	0.0041	0.0001	0.0046	0.0000	0.0051	0.0001	0.0056	0.0000	0.9387
sensor 7	0.0041	0.0006	0.0048	0.0009	0.0048	0.0007	0.0056	0.0007	0.5911
sensor 8	0.0048	0.0001	0.0055	0.0000	0.0061	0.0001	0.0066	0.0001	0.9843
sensor 9	0.0040	0.0003	0.0046	0.0003	0.0050	0.0004	0.0056	0.0004	0.7051
mean	0.0044	0.0010	0.0051	0.0013	0.0055	0.0015	0.0061	0.0015	
n	0.0913	0.0215	0.0924	0.0230	0.0899	0.0253	0.0853	0.0208	
n calculated	0.071		0.071		0.071		0.071		
difference	1.3		1.3		1.3		1.2		

Table 8.5: result from applying eq 7.10 for each sensor, for PCB coil, only output from switching converter $[Am^2]$

Voltage [mV]	1632	3σ	1632	3σ
current [mA]	74.00	1.11	74.00	1.11
sensor 1	0.0032	0.0003	0.0032	0.0003
sensor 2	0.0044	0.0001	0.0044	0.0001
sensor 3	0.0038	0.0003	0.0038	0.0003
sensor 4	0.0034	0.0001	0.0034	0.0001
sensor 6	0.0046	0.0001	0.0046	0.0001
sensor 7	0.0035	0.0003	0.0035	0.0003
sensor 8	0.0047	0.0002	0.0047	0.0002
sensor 9	0.0040	0.0002	0.0040	0.0002
mean	0.0040	0.0016	0.0040	0.0016
n	0.0535	0.0213	0.0534	0.0213
n calculated	0.061		0.061	
difference	0.9		0.9	

Another reason for the discrepancy between theory and test could also be due to the sensors. The results of the PCB-coil in table 8.5 are closer to the theoretical value however they are slighter lower than expected. It is therefore unclear what is causing the differences. In most cases the uncertainty in the measurement is such that the theoretical value falls within the bounds of uncertainty of the test.

8.4. Discussion of Results

The test results are not fully in line with what was expected. The switching converter efficiency which is much lower than expected. And the measurement of the magnetic moment are higher than expected except for the PCB coil.

In table 8.6 The results are converted to efficiency and to the factor n. The red coil has the largest efficiency as expected. The green coil is performing well, and the blue coil and PCB coil as well, but a little less efficient. All coils meet the target of 0.004Am^2 however the power expended is slightly too large due to the low efficiency of the switching converter. Nevertheless, the target of 165 MW is met for the the wire coils, red, green and blue. This target is not met for the PCB coil, however, the magnetic moment generated is much better. By reducing the actuation time of the PCB coil it could still be possible to remain within the power limit, but it would be better to redo the PCB coil based on lessons learned.

Table 8.6: results, including efficiency

	current [mA]	moment[Am^2]	n	voltage(V)	Power [mW]	Incl. conv [mW]	efficiency $[Am^2]/[mW]$
red	41.56	0.0165	0.397949775	1.43	59.4308	91.432	0.000278
blue	52.93	0.0045	0.084170131	1.59	84.1587	129.4749231	0.000053
green	48.17	0.0044	0.09131597	1.62	78.04188	120.0644308	0.000056
PCB	74.00	0.0040	0.05345564	1.632	120.768	185.7969231	0.000033

8.5. Comparison

In order to compare the different concepts they are rated on four different aspects. It has been chosen not to include mass, however that can be a significant decision component too.

None of the designs is mass optimized however. They are optimized for power efficiency, while maintaining low volume. The important aspects are as follows:

- volume
- power efficiency
- ease of construction
- modularity
- cost

The reason for choosing volume and power efficiency is that those seem to be the most precious commodities in a PocketQube. Volume is one of the first design decisions made in the process of designing a PocketQube. Once the decision to make a PocketQube is taken, the volume is known. Other than increasing the number of units the volume cannot be increased. In addition to that there is the choice between 1p, 2p, or 3p. While it would be no problem to build a 2.3 p PocketQube, launching it will be same cost as a 3p. Although it could be possible to build a pair of 1.5p PocketQubes. It is important to know that the dispenser contains 3p of PocketQube.

More power can be added by increasing the number of solar panels. However adding more solar panels requires a deployment mechanism. Deployment mechanisms require stronger attitude control systems because the surface area of the satellite will increase and also the moment of inertia. Both will require a larger torque to control the satellite attitude. A deployed solar panel needs to be pointed at the sun, which requires a better attitude control. Because the solar panel is further away from the satellite center of mass the torque required to turn the satellite increase.

Also the disturbance torque may increase because a force acting on the solar panel has a acting point further away from the satellite. Furthermore deploy-able solar panels add mission risk in case of failed deployment or, making it harder to recover from an attitude upset because the solar panels are unlit.

For all of these reasons it is important to have power efficient torquers that can generate a lot of torque with a modest amount of power. The maximum power usage of a system is also important but if a high efficiency system is used with a high maximum power the total power usage will be lower than for a low efficiency system with a low maximum power. The high efficiency system will just operate less frequently.

Ease of construction is very important. The satellite is normally built by students not craftspeople. As they have little experience with the production process the students can not make products of the same quality if they need to rely on hand made items. On the other hand cost of construction is mostly materials and machinery rather than labor. Nevertheless time required for construction cannot be very long because students will be spending only a short time on the project. This also means they have less opportunity to build experience.

The performance of the PCB coil is worse than the blue and green coils. This could be turned around by using six layers of the PCB for coils. However that can be improved because right now only 4 layers of the PCB were used. Furthermore, just as the red coil outperforms the blue and the green coil because it is larger, the PCB coils in the walls of the satellite will outperform the coil in the ADCS board, because they are larger. Both systems therefore perform similar. However the potential for improvement is larger in the PCB coil.

When it comes to ease of construction the PCB coil definitely wins. Coiling so many layers of wire proved to be quite hard, and it is still not solved satisfactorily to the point where the coils can be used on a flight model. At the same time, the fact that the trace thicknesses in the PCB proved to be wrong is also a cause for concern that would be needed to be solved, should the system be used as a flight system. Also important is that the manufacturing of the coil in the dedicated board was easy, but integrating it into a PCB with already a different function is much more difficult. This is one of the reasons the wire coil system was chosen as the system to go on Delfi-PQ. This integration of multiple functions will be even more complicated when one would try to use existing currents. Similarly using a ferromagnetic coil would increase the difficulty of construction compared to the current wire coil system.

The volume of the PCB system is definitely less than the wire coils. The wire coils take up a considerable volume. The same would be true if the wire coils had a ferromagnetic coil. The volume would likely be even larger, because the shape of the coils would have to change.

Future mission adaptability is a parameter that is supposed to indicate how much the system can be changed according to changes in the requirements. For the wire coil system efficiency drops extremely fast if volume is reduced. Also the smallest wire available is used for the system, which means changing the wire thickness is impossible. When it comes to the PCB coils almost every parameter can be changed. For example the copper traces on the PCB can be made slightly wider or narrower to control the resistance of the coil. This means that the PCB coil can be modified more easily to meet changing mission requirements, and can be optimized further.

8.6. Trade Off

The trade-off between the concepts is not of consequence for Delfi-PQ. The prototype system for Delfi-PQ was made based on a series of design choices. In the end only one concept was left. All other concepts were discarded therefore no trade-off was done.

However, in order to make this work of use for future satellites this trade-off table is presented to help choose between different concepts. The SCU concept was not built for reason of lack of modularity. This shows that modularity can be an important consideration. In order to really test the concept it would have been required to integrate it into other subsystems in the satellite which would have been problematic. The constructability and cost of the ferromagnetic core was the reason that concept was not built. Cost and constructability cannot be quantified at this point, but a qualitative judgment can be made. Having a PCB made cost less than 3D printing of the spools, therefore the Air Core is considered to be more expensive. The cost of the ferromagnetic core is not known precisely but it is expected to be a lot more expensive.
The volume of the ferromagnetic core is larger than the air Core because of the need of long narrow, torquer rods.

The efficiency of the Air core is better than the PCB coil, but, the efficiency of the PCB coil system as a whole will come close to the Air core system, because the coils embedded in the walls will be more efficient than the one in the test. The result from the test is in the trade-off table. but the efficiency is yellow for both systems indicating a similar performance.
The future mission adaptability of the ferromagnetic core is not so good, however, the performance is stronger than the other systems therefore it needs to be adapted less, therefore it is colored blue.

For the purpos of the trade-off a magnetorquer is considered that is part of the power system. The power system accepts a loss of maximum 100 milivolt on a current of 1 Amperé. The current is guided through a coil on a PQ board, similar to the one used for the PCB coil, which consists of 4 loops, one on each layer. The trace width is 2.5 mm which is quite wide but results in a low resistance. The internal area of the coil is 4500

mm^2 including all loops. That means that n is equal to 0.0045, and the magnetic moment is 0.0045[Am^2]. The resistance of the trace is 0.0002 Ohm/mm and the trace is 528 mm long. If the resistance of the switch can be kept low, that means the additional resistance is 0.106 Ω. The power is thus 106 mW. This system should be optimized further, but does give some insight in the efficiency of such a system. Similar to the PCB coil this system will gain in efficiency when implemented in the wall rather than the internal PCB, however with such an implementation it is not very much better than the PCB coil. This is somewhat surprising since reducing the voltage should improve the efficiency. However increasing the number of loops also increases the efficiency. Therefore a balance should be found in the amount of current and the number of loops.

Trade-off	Air Core	PCB Coil	Ferro-Core	SCU
Efficiency([Am^2]/[mW])	0.000056	0.000033	0.00025	0.000042
Volume[mm^3]	20	0	30	0
Future Mission Adaptability	moderate	good	challenging	good
Constructability	reasonable	easier	problematic	reasonable
System integration(modularity)	perfect	reasonable	perfect	poor
System (incremental) mass	perfect 36 g	perfect 24 g	perfect 36 g	perfect 24 g
maximum moment	0.06Am^2	0.05Am^2	0.25Am^2	0.04Am^2
Cost	moderate	low	expensive	low

Table 8.7: Trade-Off table

All four concepts have different strengths and weaknesses. The suitability of the concepts therefore depends on the priorities in the design criteria for future satellites. The wire coil torquer system is perfect as a stand alone system. When a PCB coil system is chosen it is required to have PCB's with enough room for the coils, and it means that PCB's which already have a function must be designed to take into account the traces for the coil. That means that if the design for the coil is changed, the design for the primary function of the PCB might also have to change and the other way around.

When a more powerful torquer is required it is probably good to investigate ferromagnetic cores for the coils. When more power efficiency is required it is recommended to look into a system that uses existing currents to drive its coils, or the ferromagnetic cores. In this thesis it was not discovered which system is really more efficient because it was not tested. From theory either lowering the voltage or adding a ferromagnetic core will create a torquer that is more efficient than the two concepts tested in this thesis.

Volume is very important in a PocketQube because it is so small. A magnetorquer with ferro-magnetic cores will occupy more volume than other wire coil torquers. A torquer system with coils integrated into PCB's will take up much less volume, but it is required that other subsystems make room for the coils on their PCB.

Based on the potential for improvement and the small volume, if the next Delfi satellite resembles Delfi-PQ it is best built with a magnetorquer based on coils embedded in the PCB's, depending of course on the mission requirements. But this comes at the cost of a loss of modularity, because the magnetorquers need to be integrated into the walls of the satellite. But the loss of modularity will result in a better power efficiency and a large increase in internal volume.

9

Conclusions and Recommendations

In response to an external objective of creating a magnetorquer for Delfi-PQ and to further the academic interest in PocketQubes, the choice was made to investigate what would be a good magnetorquer for a PocketQube. The method for this research was to develop a number of concepts and compare them.

The main research question for this thesis was,What is the most advantageous magnetic attitude control system for reducing angular rates of a PocketQube? By using the methodology of case studies it is possible to provide insight in the answer to that question.

Magnetic torque is useful to satellites because it is an external torque, and it can be generated by electronic currents. That gives it an edge over other means of satellite attitude control which can be saturated or run out.

The development of the concepts includes the construction of the different concepts, within the framework of Delfi-PQ. The reason for including the construction is that the construction of a device is important. When it is constructed other drawbacks are discovered compared to only designing a torquer. Furthermore, due to the external objective it was required to build and test at least one concept. The objective of the thesis therefore became to compare different magnetorquer concepts for PocketQubes, construct them and test them, in order to answer the research question.

For a CubeSat commercial modules are available that provide magnetic torque. This is not yet the case for PocketQubes. Because a PocketQube is different from a CubeSat, the CubeSat solution is not necessarily also best for a PocketQube, therefore also concepts different from the concept generally used for CubeSats are explored.

The methodology of answering this question was to design, build and test different concepts. In total four different concepts were considered:

1. A torquer made out of copper wire, without a ferromagnetic core, thus an air core magnetorquer.
2. A torquer made out of coils printed on a PCB, also an air core, which will be referred to as a PCB coil.
3. A torquer made out of copper wire, with a ferromagnetic core, thus a ferro-core magnetorquer.
4. A coil that is a secondary utilization of an existing current, which is also made using a PCB.

Two of the torquers were built, the Air core and the PCB coil. The choice which concepts were built was determined by the needs of the Delfi-PQ program, the feasibility of constructing the concept and which concepts are interesting. Building the fourth concept would not be that different from the PCB coil.

That is not the case for he ferromagnetic core magnetorquer. It is interesting to build this torqer. However it was not built because it was expected to be costly and difficult to obtain the correct material. Nevertheless because this is the solution of choice for CubeSats it would have been nice to compare it as well.

One of the first things produced for the thesis the design a of the air core magnetorquer system for Delfi-PQ. For this thesis an actuator prototype was built that can be used on Delfi-PQ. It was not yet developed into a flight model.

The spools for this prototype were made with a 3D printer using a low out gassing polymer (Ultem 9085). The prototype performed very well, however it was found that the method of winding the wire around the spools used is not sufficient. Neatness of winding the wire is still a problem that will require attention before it can be launched. Based on the hardware prototype it is possible for the control software designers to have the correct parameters, including magnetic moment generated, and minimum actuation time.

Building the second concept, the PCB coil had it's own challenges. First a software code had to be written to design the PCB. The PCB for this project was more simple than a flight model would be because a flight model PCB would have more than one function.

One thing that was discovered is that the thickness of the copper layers on a PCB is not always as expected. The PCB coil performed well but there is more opportunity for improvement, compared to the air core which is already very optimized. Although the performance of the PCB Coil did not match that of the air core, it came very close.

One of the goals of the thesis was to build a design independent testing method. This was achieved by making a test board mounting nine magnetic sensors. This was built on a PCB using MLX90393 three axis magnetic sensors. For this purpose it is very important to know the precise location of the sensors with respect to the torquer.

After the test board was made, it was then used to test the designs that have been built. The test board can easily be used with the software especially written for it during the thesis. The reason for this is that code available to control the sensor is intended for use of one sensor only. This could be adapted to multiple sensors but then each sensor would be operated sequentially. The software used in this thesis allows all sensors to be operated at exactly the same time.

The sensitivity of the test board is sufficient for testing the magnetorquers. It should be able to measure magnetic field strong enough to impact attitude control, such as other satellite subsystems hat may generate magnetic fields similar, but less powerful as the magnetorquers. All magnetic fields will affect the attitude control and it is therefore important to know them.

In order to do that successfully it may be good to further automate the analysis of the measurement results to make it fully plug and play. The data analysis can also be improved. The sensors are used mostly individually in this thesis but there may be an opportunity to learn something from the combination of the different sensors, and by making a second generation of the board with more sensors. Also the uncertainty in the measurements was quite large, it may be possible to improve this by changing the position of the magnetorquer with respect to the test board or by modeling the magnetorquer more extensively.

After the tests were done the four concepts were compared in a trade-off table. This trade-off table is meant to help future PocketQube satellite designs. All four concepts have different strengths and weaknesses. The suitability of the concepts therefore depends on the priorities in the design criteria for future satellites. The wire coil torquer system is perfect as a stand alone system. When a PCB coil system is chosen it is required to have PCB's with enough room for the coils, and it means that PCB's which already have a function must be designed to take into account the traces for the coil. That means that if the design for the coil is changed, the design for the primary function of the PCB might also have to change and the other way around.

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Based on the potential for improvement and the small volume, if the next Delfi satellite resembles Delfi-PQ it is best built with a magnetorquer based on coils embedded in the PCB's, depending of course on the mission requirements. But this comes at the cost of a loss of modularity, because the magnetorquers need to be integrated into the walls of the satellite. But the loss of modularity will result in a better power efficiency and a large increase in internal volume. At the cost of an even further loss of modularity it should be explored if the magnetorquer can become part of the satellite power system, using electrical currents already existing in the satellite.

Further recommendations The switching converter needs more attention before it can be used for a magnetorquer. By using a different converter it may be possible to reduce power consumption a lot. The current converter has an efficiency of about 65% where 80% to 90% efficiency should be possible. It may be needed to slightly increase the voltage across the magnetorquers to increase converter efficiency. However increasing the voltage will decrease the efficiency of the magnetorquer itself. Selection and design of the switching converter was outside the scope of the thesis.

As mentioned, in order to increase the power efficiency of the magnetorquers it is recommended to look into using existing currents in the satellite and redirecting them through a coil. This way a very low voltage drop coil can be used, which would increase the efficiency of the magnetorquer. A magnetorquer operates efficient at low voltage and high current provided the current is not too high, requiring thick connections.

In order to upgrade to a flight model of the prototype for Delfi-PQ it is important that a better way is found to wind the wire around the spools. This could be left to a specialized company or by changing the wire winding method. If a coil is embedded in a PCB, it is important to make sure that the trace thicknesses are correct. The best way to ensure this is by using only internal layers for the coil.

Thermal vacuum testing of Ultem 9085 prototype to avoid breakage due to gas inclusion. This was not part of the thesis but it should be tried for the flight model.

In a next iteration of the test board it would be good to have more user friendly connector cables between test board and Launchpad. Another thing that could be improved in the test setup is adding more sensors. It was also found that the temperature of the sensors affects the measured magnetic field. The sensors were calibrated at the same temperature as the measurements were taken, therefore it was assumed the measurement results were not affected. The sensor manufacturer however gives options for temperature compensation, this could be included such that variations in temperature have less effect on the measurements. This was not done in the thesis work because it was additional work to implement correctly and did not give much benefit to the thesis.

Furthermore it is recommended that all satellite systems that consume or generate electric current undergo magnetic testing. The test developed in this thesis cannot perform this task very accurately, but the hardware may already be good enough if some time is invested in the software and calculation method. This knowledge can then be incorporated in the design of the satellite attitude control. By doing this, the design may be adapted such that the net disturbance torque is minimized. This can further reduce the power needed for magnetic attitude control.

An additional advantage of the test setup is that, once a flight model is completed the orientation of the torques can be checked independently. This means that the flight model can be verified to operate according to its software. If the connection of a wire is reversed that also the torquer would operate opposite to what the software instructs. Also it can be verified that the flight model achieves the required magnetic moment.

Because of the low voltage drop in the secondary current concept this is a very interesting concept for a PocketQube. Based on the work done in this thesis for the PCB coil it has become more feasible to pursue this concept. The experience with coils as a trace on a PCB will help, however for this concept the real challenge will be to integrate it in the other subsystems. This goes much further than integrating the coil into the PCB of another subsystem, this also requires to change the electrical circuit of the power subsystem. That also means that if the magnetorquer has a failure, the flow of power in the satellite is interrupted, which would likely cause loss of the satellite.

If the ferromagnetic core concept is explored further collaboration with the department of novel aerospace materials recommended to make a ferromagnetic core for the magnetorquer. This idea was not explored in this thesis, but likely faculty already has the right equipment and knowledge about materials to produce a magnetorquer.

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A Glossary

A copy of this glossary can be found in the appendix for easy access.

A :	Area, quantity with unit $[m^2]$
A :	Amperé, SI base unit of electrical current
ADCS :	Attitude Determination and Control System
Am^2 :	Amperé meter squared (unit of magnetic moment)
AWG :	American Wire Gauge
COTS :	Commercial of the shelf
CubeSat :	nano satellite adhering to CubeSat standard
d :	arbitrary distance
Delfi-PQ :	pico satellite from TU Delft
I :	electrical current
I2C :	I^2C is a common serial communication protocol
kg :	kilogram, SI base unit of mass
m :	meter, SI base unit of length
mG :	milliGauss, unit of magnetic field density where 1 $mG = 1 \cdot 10^{-7} T$
nano satellite :	satellite of mass less than 10 kg
p :	unit of size PocketQube
PCB :	Printed Circuit Board
pico satellite :	satellite with mass less than 1 kg
PocketQube :	pico satellite adhering to PocketQube standard
R :	radius
rho :	resistivity
s :	second, SI base unit of time
SPI:	simple serial communication protocol
T :	Tesla, Unit of magnetic field density$[Wb/m^2]$
U :	unit of size CubeSat
V :	Voltage, or electric potential
$[V]$:	Volt unit $[m^2 kg s^{-3} A^{-1}]$
Wb :	Unit of magnetic flux $[m^2 kg s^{-2} A^{-1}]$

PCB nomenclature	
blind via:	a connection between adjacent layers, but not all layers. blind vias are more expensive than vias.
inner layer:	a layer inside the PCB no components can be placed on this layer
layers:	the number of copper planes in a PCB. A PCB typically has an even number of layers. The more layers a PCB has, the more complex the circuit can be.
outer layer:	layer on the outside of the PCB. Surface mounted components can be placed here.
PCB:	**P**rinted **C**ircuit **B**oard, a circuit that is 'printed' on substrate material.
plane:	a synonym for layer. Typically used if a layer is used for a single purpose. e.g. a ground plane means a layer that is entirely used as a ground.
Stitching via:	A redundant via that is placed to ensure good conduction between different layers to avoid thermal stress and voltage differences due to long current paths.
thermal:	A reduction in copper area to reduce thermal conduction, for easier soldering.
trace width:	the width of a current path. The trace width determines the resistance of the trace. Traces are created by covering the entire substrate in copper and then etching away the copper between the traces. Therefore all traces in a single layer have the same copper thickness.
trace:	a current path on a PCB, formed by etching away some of the copper of the layer.
via:	a connection between all layers of a PCB.
pad:	a exposed copper surface where using solder a connection can be made with a surface mounted component.
soldermask	area of a PCB where the copper is covered in a layer that prevents adhesion of solder.

B
Render of PCB Concept

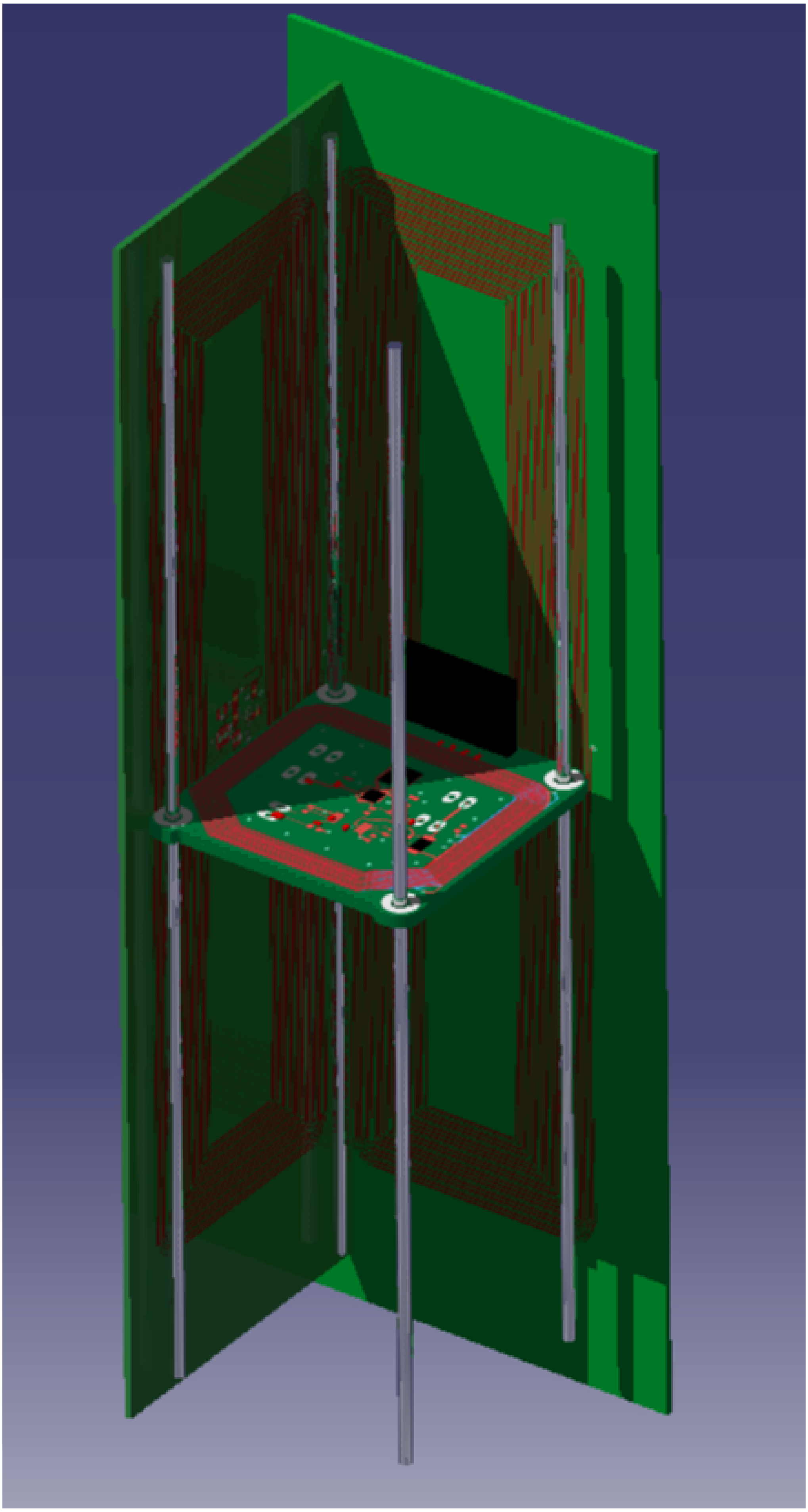

Figure B.1: Envisioned system.

C

MLX90363

Table C.1: gain options of MLX90393 [37]

Gain	Res = 0		Res = 1		Res = 2		Res = 3	
	xy	z	zy	z	xy	z	xy	z
0	0.751	1.210	1.502	2.420	3.004	4.840	6.009	9.680
1	0.601	0.968	1.202	1.936	2.403	3.872	4.840	7.744
2	0.451	0.726	0.901	1.452	1.803	2.904	3.605	5.808
3	0.376	0.605	0.751	1.210	1.05	2.420	3.004	4.840
4	0.300	0.484	0.601	0.968	1.202	1.936	2.403	3.872
5	0.250	0.403	0.501	0.807	1.001	1.613	2.003	3.227
6	0.2	0.323	0.401	0.645	0.801	1.291	1.602	2.581
7	0.150	0.242	0.300	0.484	0.601	0.968	1.202	1.936

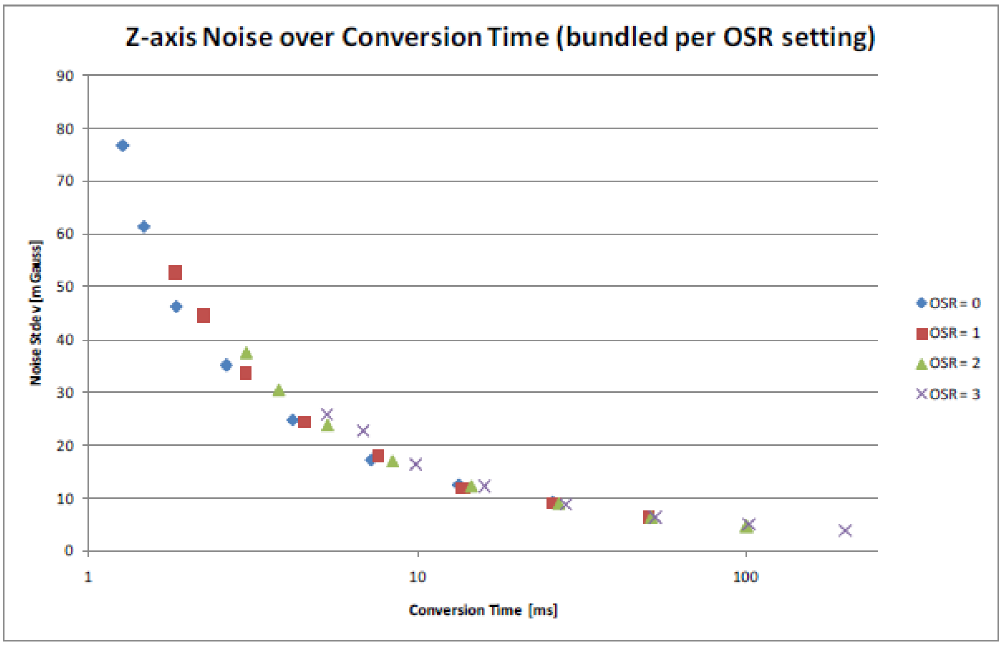

Figure C.1: Noise of MLX90393 as a function of conversion time[37]

D

Design drawings

E

PocketQube

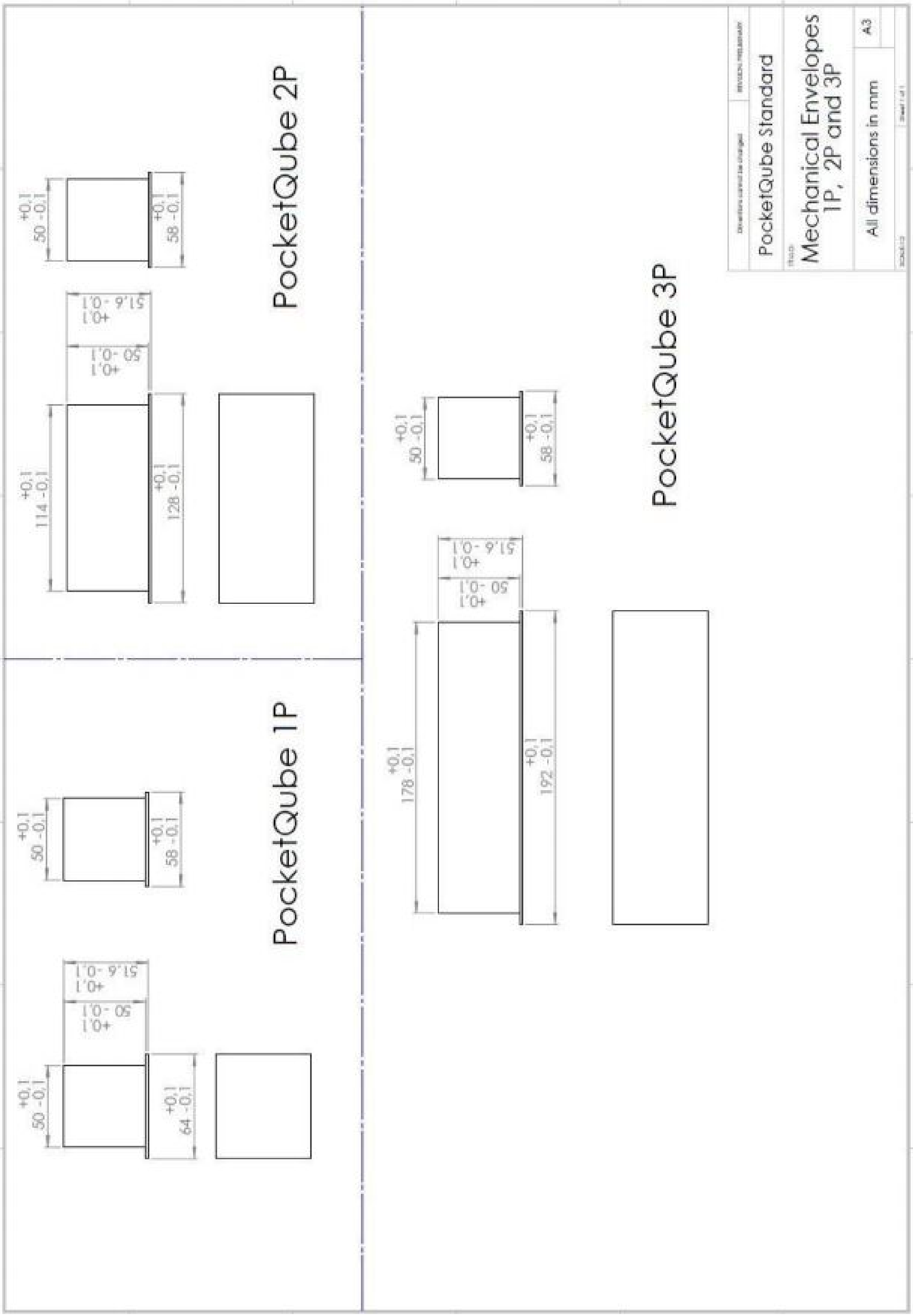

Figure E.1: PocketQube dimensions [8]