HELMHOLTZ MAGNETIC SIMULATION ENVIRONMENT

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Contents

1 Introduction

To test and validate the Attitude Determination and Control System of the CubeSat, the ADCS team decided to build a device that can generate a steady and controlled magnetic field: a Helmholtz coils magnetic simulation environment.

The Helmholtz coils are two separate coils facing each other like described in the scheme below.

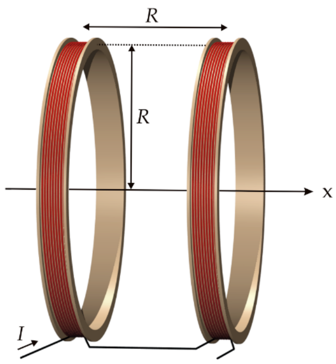

Figure 1: A Helmholtz coil pair

This combination can generate a magnetic field between the two coils that is uniform on one axis. Here is a spatial representation of this magnetic field on an orthogonal plan to the coils.

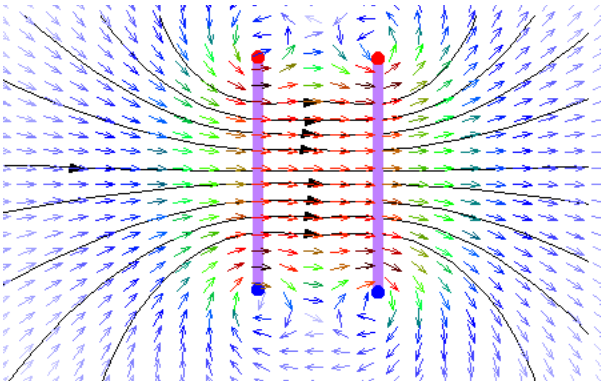

Figure 2: Magnetic field in a Helmholtz coil pair

The norm of this field is given by the following formula:

$$B_0 = \left(\frac{4}{5}\right)^{\frac{3}{2}} \frac{\mu_0 n I}{R}$$

With:

$$\begin{cases} B_0(T)\text{: Magnetic field} \\ \mu_0(kg.m.A^2.s^2)\text{: Magnetic permeability of empty space} \\ n\text{: number of windings} \\ I(A)\text{: Current in the windings} \\ R(m)\text{: Radius of the coil} \end{cases}$$

By building a device like this, it is possible to generate a magnetic field with a control on the norm and direction using the current. Thus we can:

- Test and calibrate magnetometers in a controlled environment.
- Test and validate the sizing of the magnetorquers
- Integrate those two in a CubeSat model to test our filtering and positioning algorithms
- Build a visual representation of the CubeSat progress.

2 Design

We have established two possibilities:

- A simple pair of coils to simulate a one axis magnetic field.
- An assembly of 3 pairs of coils, to have an omnidirectional magnetic field.

We eventually settled for the three axes version because the added benefits.

In those two cases, we make the choice of building square coils to facilitate the construction, the use, and the storage. However, this implies a slightly inferior ratio between the effective volume and the real volume of the device.

To build a simulation environment where we can control the magnetic field on 3 axes, we need three pairs of Helmholtz coils, placed on the 3 axis of a cube.

To limit the quantity of copper needed, we can use a version with a side of 80 cm instead of the initially planned 1m. This will of course give us a reduced usable volume of 40x40x40 cm instead of 50x50x50 cm.

The advantages of this 3 axis version of the device:

- We can control the direction of the magnetic field generated;

- We can entirely cancel the geomagnetic field ;
- The testing will be in a significantly more realistic environment.

However, the cost is more consequent, particularly because of the quantity of copper needed and the aluminium for the coils.

A mathematical model is required for the sizing of the simulator.

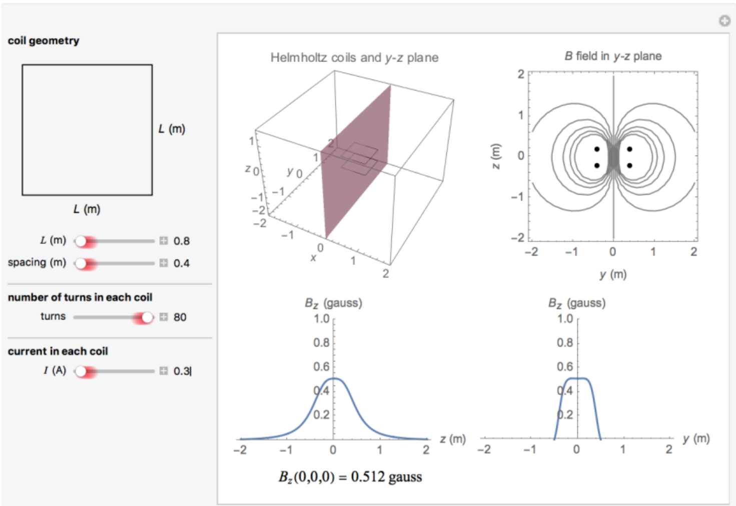

Figure 3: Simulation of the magnetic field generated with 300mA

With a current on 300mA, we get a constant magnetic field of 0.5 Gauss. This is enough to cancel the magnetic field of the earth.

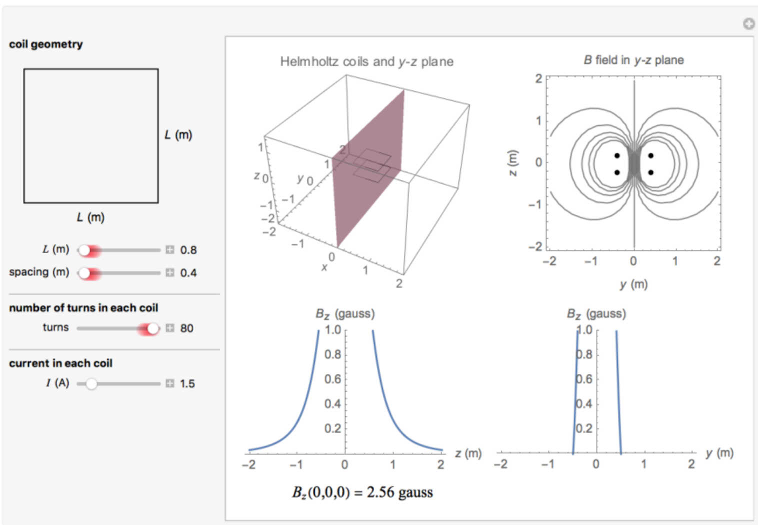

Figure 4: Simulation of the magnetic field generated with 1.5A

With a current of 1.5A (which corresponds to input voltage of 30V), the magnitude of the magnetic field is over 5 times the earths magnetic field.

These simulations are for one pair of coils. In reality, the coils are orthogonal to each other and the current can be reversed, meaning that the superposition rule gives us a fully orientable magnetic field with 5 Gauss amplitude (at 30V).

2.1 Interests of the Helmholtz simulator

As we previously indicated, the project presents many interests for validation and prototypes of ADCS.

2.1.1 Magnetometers tests and calibration

The CubeSat uses 3 magnetometers to determine the magnetic field around it, and calculate the attitude adjustment.

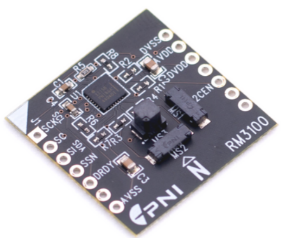

Figure 5: PNI RM3100 3-axes magnetometer breakout board

The simulation space, made with Helmholtz coils could let us test the efficiency and the accuracy of the magnetic sensors on 3 axis. Then we can verify the metrological data, and their accordance with our specification. More importantly, because the magnetometers only give a discrete value that is proportional to the magnitude of the magnetic field, they need to be calibrated to convert this value (according to the datasheet of the PNI RM3100).

2.1.2 Magnetorquers

The magnetorquers are coils placed in the CubeSat that can, with an electrical current, generate torque in space with the magnetic field.

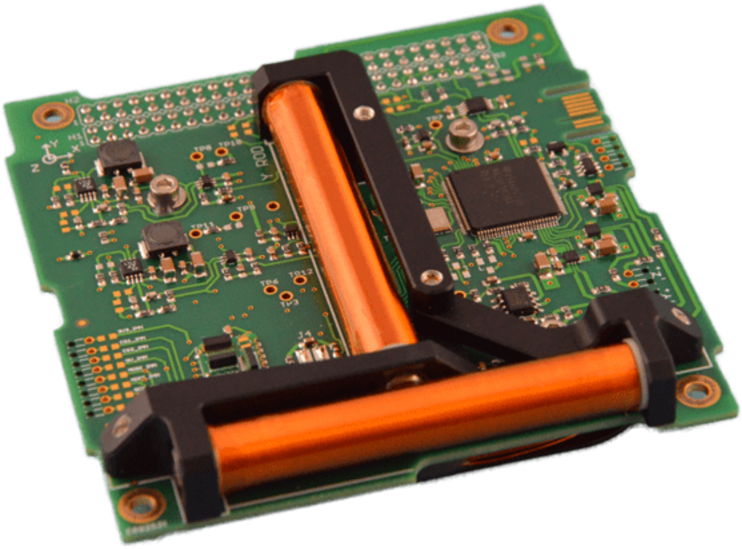

Figure 6: Magnetorquer module from CubeSatShop

To reproduce the theory with magnetorquers, we will put the cube in the Helmholtz coils on its bracket that will free it out for movements. We will generate a magnetic field 10 times higher than the geomagnetic field, and we will send commands to the magnetorquers to verify the amplitude of the torques generated.

The Helmholtz environment will eventually help us for the sizing of the magnetorquers.

2.1.3 System tests

Finally, the most important test that we plan for this year with the simulation environment is a series of tests on all the components of the CubeSat: sensors, magnetorquers and algorithms.

Precisely, it is question here to simulate a functional model of the satellite and to measure its capacity to position itself under a range of stimuli.

This step will result in two fundamental elements:

- This will complete our work of theory and software modelling by physically verifying the behaviour of the model. Either if limits are known, this will lead to a measurable evaluation of our activities.

- This model is a device that will visually represent the progress of our work. And then, the future teams will be able to use this model and simulator for other purpose. For potential presentations to professors, companies, our school and other students, this will demonstrate the efficiency of our work.

2.2 System specification and features

The system design specifications for the Helmholtz coils simulator are the following:

Requirement	Value
Volume of the constant field zone	64L (40x40x40cm)
Output magnetic field range	-5 to 5 Gauss (on each of the 3 axes)
Input voltage range (per coil)	20V to 60V
Max. input current (per coil)	3A
Coils equivalent series resistance (ESR)	22Ω to 23Ω
Time of assembly and disassembly	Less than 5 minutes
Maximum variation of the field	0.1 Gauss

In addition to these quantitative specifications, there were also qualitative constraints:

- The magnetic field should be fully controllable through software;
- The system should be modular, any part must be replaceable;
- The usage of the system to program any arbitrary magnetic field should easily be done by future students of the CubeSat project;

3 CONSTRUCTION

3.1 Mechanical build

3.1.1 Coil structure

As discussed earlier, we chose the following dimensions for our simulator: 80cm square coils with 80 turns. This adds up to about 256m of copper per coil.

The wire used for the windings is 0.5mm (AWG 24) diameter copper enameled magnet wire. One important equation for the choice of this wire is the resistance:

$$R = \frac{\rho L}{S}$$

This means that with a lower gauge, a lower input voltage would have been required for the same amperage which makes it easier to drive. However, the total mass (and cost) of copper has a quadratic growth with the diameter of the wire. A diameter 0.5mm fits well within our design constraints. Furthermore, 256m of this wire corresponds to just under 500 grams, a standard mass for spools of magnet wire.

To wind these coils, the frame is made out of aluminum profile, U-shaped. The outside width of the profile is 7.5mm, which is enough to store about 140 turns of our wire. It is also fairly rigid and inexpensive. We used plastic brackets to assemble the aluminum profile to form the structure of our square coils.

In order to ensure that the assembly and disassembly time meet our constraints, we designed a clip that attaches the 6 coils of our Helmholtz simulator together and makes a rigid cage.

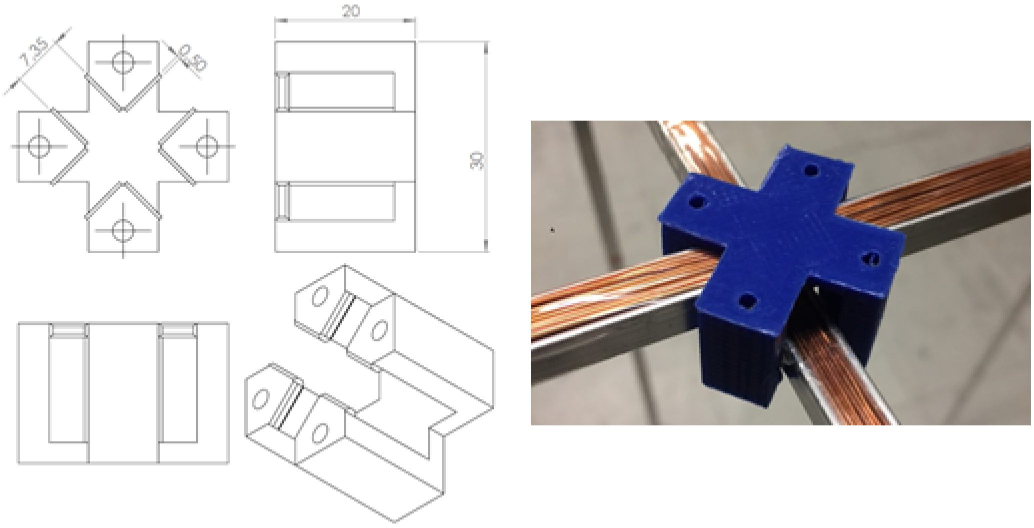

Figure 7: Clip to hold the Helmholtz coils structure

This friction-fit can support well over the 500 grams of the coils and can be 3D printed in about 20 minutes.

With the help of the instruction manual we wrote for the future ADCS and other CubeSat teams, the structure can be assembled and disassembled in about 5 minutes.

3.1.2 Free spinning device

Another mechanical concern was to make a device that allowed a model of the CubeSat to be free spinning in every direction.

Our first attempt is a gyrostat. It uses 3 disks with ball bearings to create the 3 degrees of freedom required for the free spinning

Figure 8: Gyrostat SolidWorks render

It was 3D-printed in PLA and assembled using Acetone welding. Although this design achieve free spinning of the center sphere, the few imperfections in the 3D-printing process makes it prone to balance issues. It could be balanced and used for our purpose, but we chose to try another method.

Our second attempt uses is an air-bearing. It uses compressed air to lift the sphere from the support (less than 0.1 mm).

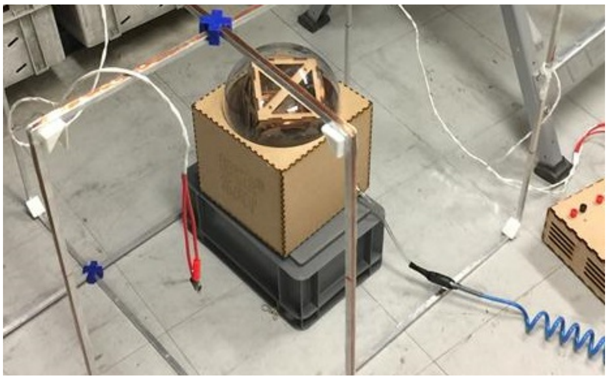

Figure 9: Air bearing with inlet hose

The major flaw of this solution is the equipment required to run it: a 40 liters compressor tank at 120 psi can run it through an air regulator for less than two minutes without needing to run the motor. When the 2 horse power motor start running, it creates an uncomfortably loud noise. Also, the turbulent flow of air that lift the sphere create a slight wobble, which is a source of friction. This problem could have been solved with a better air delivery system, but the solution was discarded due to its impractical nature.

Finally, our third attempt, and the design we eventually validated during our testing is the simplest. The CubeSat model (or any device that we want to test in the magnetic field) is placed in a sphere that floats in water bassin.

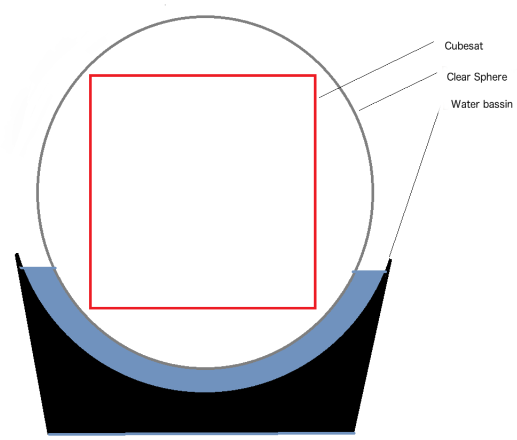

Figure 10: Sectional drawing of the water bearing

Our testing shows that, as long as the sphere is well balanced, it is able to free spin.

The fluid friction force is $F = -kv$ where v is the velocity and k is a constant proportional to the viscosity of the fluid. Because in our case, both k and v are low, the effect of this force is small enough to allow the very low torque created by our magnetorquers to move the sphere.

3.2 Electronics circuit

A circuit is required to control the current that goes through the 6 coils and therefore the intensity of the magnetic field.

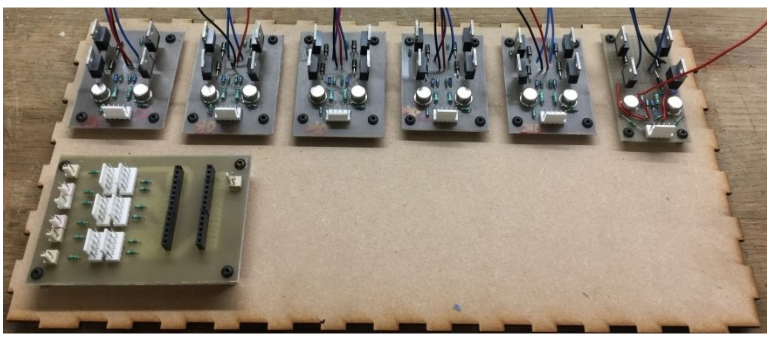

Figure 11: Circuit for the Helmholtz simulator

The subsystems are the following:

- Logic computational unit: this board drives the power modules according to the software that is loaded on the micro-controller.
- Power H-Bridge: these modules control the amount and the direction of the current that goes through each coil;

The circuit for each of these subsystems will now be detailed.

3.2.1 Power H-bridges

Because of our high voltage and high inductance requirements, the general purpose readily available motor driver integrated circuits would not have worked in this case.

This is the complete circuit of each of the modules:

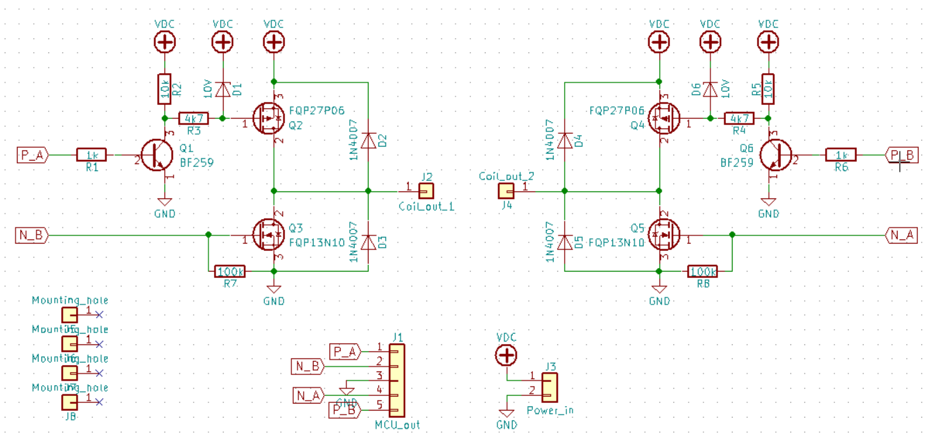

Figure 12: Circuit schematic of the H-bridge

This is the state table for each input combination of the circuit. A logic '1' is a 3.3V to 5V signal, and '0' is 0V.

P_A	P_B	N_A	N_B	*State*
1	X	X	1	Forbidden (short circuit)
X	1	1	X	Forbidden (short circuit)
0	0	0	0	Off
1 (or PWM)	0	1	0	On (forward)
0	1 (or PWM)	0	1	On (backward)

All of the other input configurations are not relevant as they produce no effect on the output. They should also be considered as forbidden states to ensure the coherence of the software.

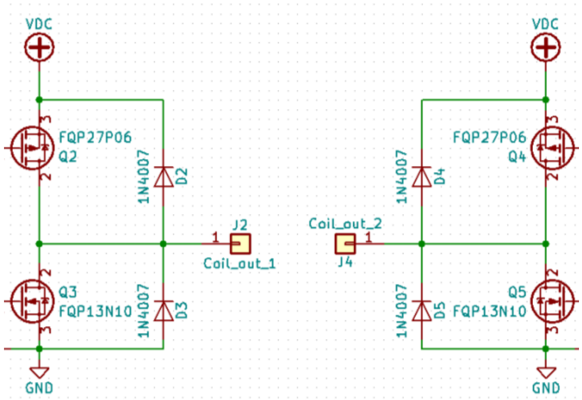

Figure 13: MOSFETs part of the H-bridges

This is the standard H-Bridge configuration with additional fly back diodes. These diodes ensure that the inductive spikes created by the coils do not destroy the MOSFETs. The diodes we chose are 1N4007 because of their maximum reverse voltage of 1000V.

Concerning the MOSFETs, the N-channel ones are FQP13N10, rated for logic-level threshold. With their 140 $m\Omega$ R_{DSON}, their power dissipation is 65W without any heatsinking. The P-channel are FPQ27P06 with 70$m\Omega$ R_{DSON}.

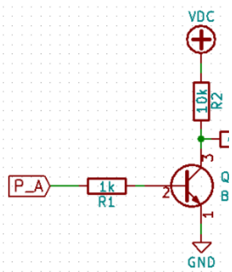

Figure 14: NPN bipolar junction transistors part of the H-bridges

Next, this stage drives the N-channel MOSFETs by outputting either 0 or VDC on its gate. The values of the resistor are computed so that the NPN transistor is always in saturation.

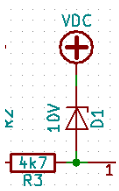

Figure 15: Zener diode part of the H-bridges

Finally, because the absolute maximum V_GS of -25V of the FPQ27P06, we added this

Zener diode that caps the V_GS to -10V, no matter what the input voltage. R3 and R4 determine the input range. With 4.7k, the minimum voltage is about 20V to ensure the stability of the diode, and the maximum voltage is about 60V to limit the power that goes through R3 and R4. This is the equation:

$$P_{max} = \frac{(V_{DC} - V_Z)^2}{R}$$

Using the open-source CAD software Kicad, we designed a compact, single-sided PCB to build 6 identical modules.

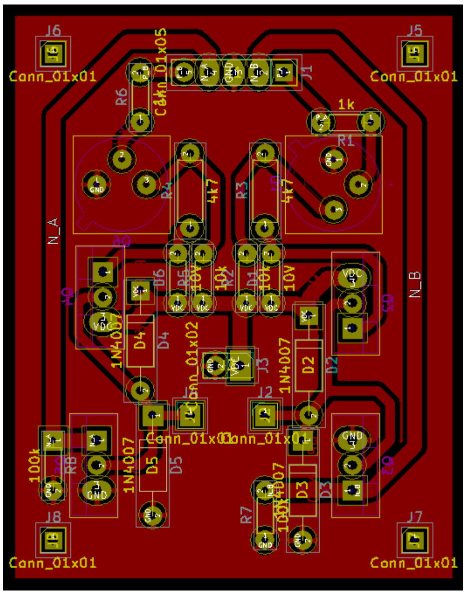

Figure 16: PCB layout of the H-bridge circuit in Kicad

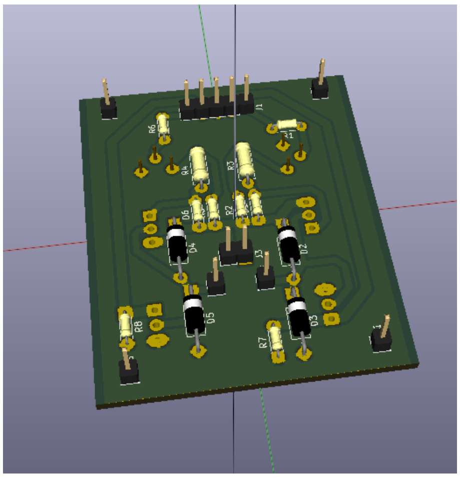

Figure 17: 3D-render of the PCB of the H-bridge circuit in Kicad

To etch the PCBs, we used mechanical engraving with the Fablabs CIF machine.

3.2.2 Logic unit board

The purpose of this board is to run the software and drive the H-bridges. It is based around an Arduino Nano with an Atmel ATMEGA328P mainly because of the cost and the simplicity of the programming tool-chain compared to other more powerful micro-controllers.

We also used Kicad to design a PCB to layout the connectors to the LEDs and the power modules.

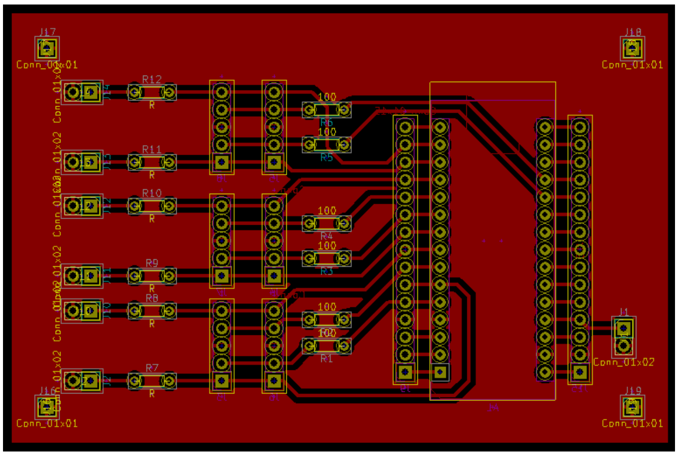

Figure 18: PCB layout of the logic unit circuit in Kicad

This simple board was etched using a chemical process, with the machines available at the ECE fablab.

Figure 19: Etching of the logic circuit board

The software that we developed on this board will be discussed in the next section.

3.2.3 Enclosure and safety

To protect the electronics, we designed an enclosure that was cut using a laser. Safety warnings were also engraved.

Figure 20: Enclosure for the Helmholtz circuitry

The box has 24 4mm banana plugs: 12 for the H-bridges power input and 12 for the coil outputs. It also features a 100A circuit breaker. It is a DC equivalent to an emergency switch, often limited to 10A AC.

The LEDs indicate the status of the coils: they light up to indicate the magnitude and the direction of current.

3.3 Software

If the power modules were poorly driven, short circuit could occur, thus creating dangerous situations. To avoid this, we created a set of low-level functions that set the pins to the correct state.

To program the Helmholtz coils, the user can simply provide a three dimensional waveform of the desired magnitude of the magnetic field. The software reads the arrays and handles all of the low level tasks: calculation of the PWM duty cycle, changing the pins states, etc. There are also built-in safety procedures to avoid the sudden collapse of the magnetic field, which might be dangerous for the user and the electronics.

3.4 Result

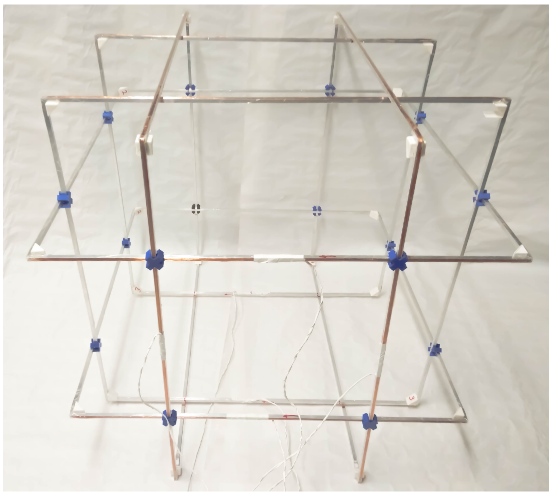

Figure 21: Final Helmholtz coil simulation system

To validate our simulator, it is necessary to check two aspects of the magnetic field it generates:

- The constancy of it with a fixed input current on each of the three axes
- The full control of the magnitude of the field on each of the three axes

3.4.1 Constancy of the field

To make sure that the field in the working volume is constant, we ran several series of tests. For each of the axes, a constant current is fed into the pair of coils, and a sensor is moved within the cage.

Those tests were done with three different input magnetic field: 0.5 Gauss, 1 Gauss and 2 Gauss.

For instance, this capture was taken during a back and forth movement of the sensor along the X axis, while the three pairs of coils were powered to reach 2 Gauss (200 μT).

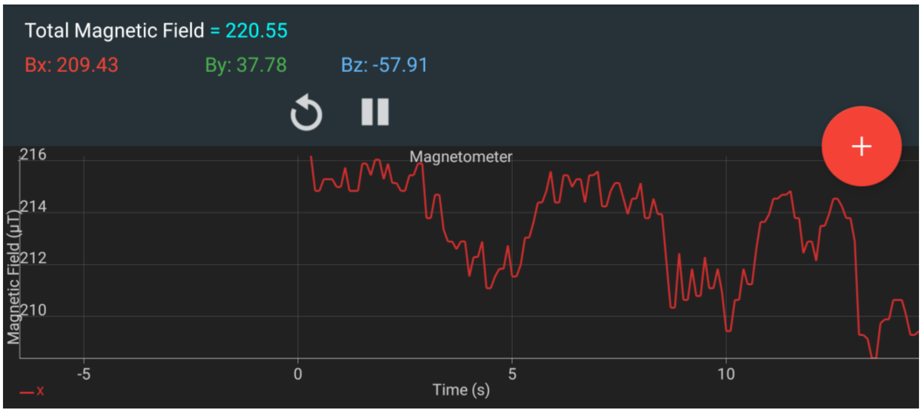

Figure 22: Plot of the magnetic field while the sensor is moved along the X axis

The field is very constant: within 0.06 Gauss of variation in the X axis. This matches our specifications.

To give more emphasis on this result, we disconnected the system at t=15s. With the graph re-scaled, this constancy gets more obvious.

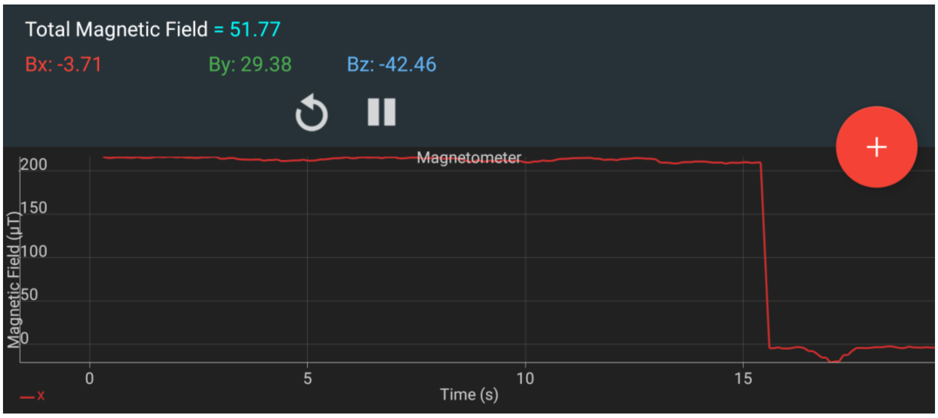

Figure 23: Plot of the magnetic field while the sensor is moved along the X axis

With the same test performed on the three axes, we validated the constant nature of the magnetic field in our Helmholtz simulation environment. This is a very important result as it proves that the coils are well wound, that the electronics manages to power them with a constant current, and that any testing we will later do in the simulator is meaningful no matter where it is placed in the working volume.

3.4.2 Control of the magnetic field

After it is proved that the field is constant within the working zone, we ran another set of test to check the control that we have on the generated field.

The experimental protocol is the following: a description of several magnetic field waveforms is done in the software, and a sensor is placed in the Helmholtz coils. If the measured waveform corresponds to the one described in software, it proves that we have control over the magnetic field.

For instance, we described in the software triangle waveform for the magnitude of the X axis magnetic field. This waveform has an amplitude of 2 gauss (200 μT) and a period of 7.5s.

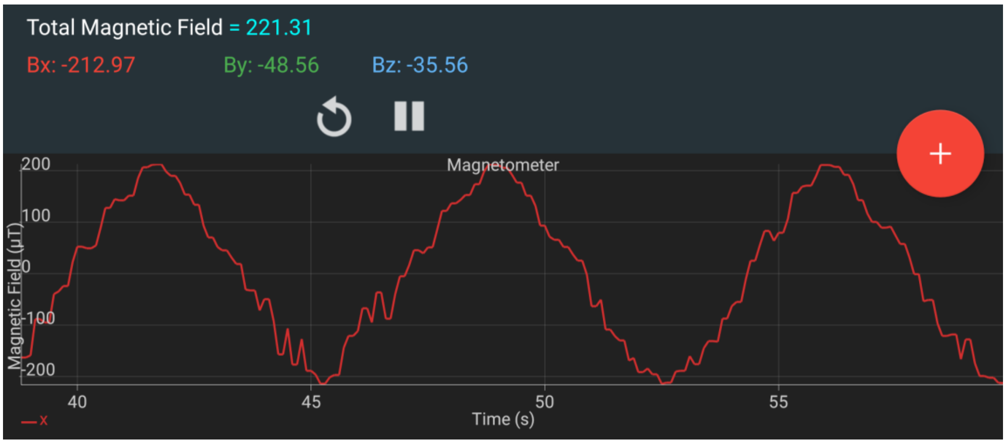

Figure 24: Plot of the magnetic field with a triangle waveform

As shown by this capture, the waveform corresponds to the one we described in software. With the testing of the magnetic field with different waveforms in each of the three axes, we validated our control of the Helmholtz simulation environment.

4 CubeSat model and sensor analysis

In addition to the Helmholtz simulation environment, we designed and built a model of the CubeSat to study various aspects of the ADCS: the sensors and the magnetorquers.

Figure 25: Model of the CubeSat with its motherboard

It has a motherboard with:

- Arduino Nano: this microcontroller board is just for fetching the data and driving the magnetorquers. It is not part of the system under test
- H-bridges: we used readily available L6202 H-bridge motor driver chips to power the magnetorquers. Again, they are not part of the system under test;
- Bluetooth module: to get the data from the board while it is spinning in the simulator, we used a Bluetooth module
- RM3100 magnetometer and ITG3200 gyroscope: these sensors were picked according to their features, and are tested by this model

It also features three magnetorquers with 600 turns of 0.2mm enamelled wire with a radius of 80mm

4.1 Sensors

4.1.1 Magnetometer

For the model, we chose the PNI RM3100 sensors. These sensors are use in other successful CubeSat. They were preferred for their accuracy, low noise (inferior to 20nT), high sensitivity (26nT) and very high linearity over the field measurement range.

Although they require an initial calibration, they seem well fitted for our need. Using an address selection pin, two of them could be fitted on a single I^2C bus for redundancy.

In our test setup, we managed to reach the accuracy written in the datasheet, and therefore conclude that this sensor is a viable choice for the CubeSat.

Unfortunately, on the particular breakout module we chose only supports the SPI bus and not the I^2C bus that we initially planned to use. This is because the bus choice pin is hard-wired to ground, and there is no way to change this.

4.1.2 Gyroscope

The ITG3200 gyroscope is a digital output MEMS with a high resolution and a full-scale range well within our specifications. Additionally, it is low power and outputs its data through a IšC bus.

Like the RM3100, an address pin can change the address to fit two or more for redundancy (if required).

Further testing is required with the simulator to validate their usage on the final CubeSat ADCS module.

4.2 Magnetorquers

For this model, we also designed magnetorquers for the three axes rotational movement. These where our sizing calculations:

4.2.1 Magnetic moment and magnetic force

The magnetic moment ($\vec{\mu}$) characterizes the magnetic intensity of the source : $d\vec{\mu} = \vec{J} dV$. It is given in $A \cdot m^2$.

A magnetic dipole in a magnetic field $\vec{B}$ is subjected to a magnetic moment ($\vec{\tau}$) and a force ($\vec{F}$):

$$\vec{\tau} = \vec{\mu} \wedge \vec{B}$$

$$\vec{F} = \vec{\nabla}(\vec{\mu} \cdot \vec{B})$$

Furthermore, the potential energy is $Em = -\vec{\mu} \cdot \vec{B}$.

4.2.2 Case of a solenoid

A solenoid has a magnetic moment:

$$\vec{\mu} = N \times I \times \vec{S}$$

Where N is the number of turns, I is the current intensity and $\vec{S}$ is the surface of the coil (the direction of the vector is determined by the "right hand rule").

Therefore, we can calculate the forces that apply on a solenoid in a constant magnetic field:

$$\vec{\tau} = N \times I \times \vec{S} \wedge \vec{B}$$

$$\vec{F} = \vec{\nabla}(N \times I \times \vec{S} \cdot \vec{B})$$

The following figure is a representation of the torque applied on an energized coil, according to this formula.

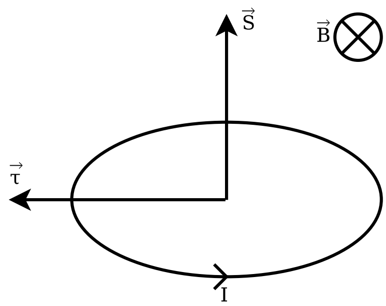

Figure 26: Torque on a current loop in a magnetic field

The linear force can be ignored due to its very low value compared to the velocity of the satellite.

4.2.3 Norm of the τ vector

We consider the magnetic object rotating around a single, fixed axis. The $\vec{B}$ field is supposed to be constant.

Let $\theta(t) = (\widehat{\vec{\mu};\vec{B}})$ and τ the algebric norm of $\vec{\tau}$. We have the relation:

$$\tau = \|\vec{\mu}\| \times \|\vec{B}\| \times \sin(\theta(t))$$

The sign of $\sin(\theta(t))$ determines the direction of the torque generated by the magnetic moment. In addition, note that $\vec{\tau} = \vec{0}$ every time $\theta(t) = 0[\pi]$.

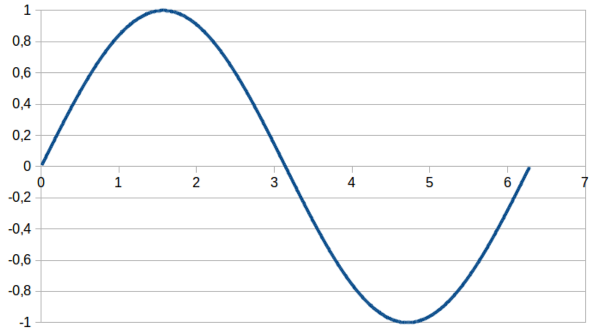

Figure 27: Norm of the torque over a full rotation

Over a full period of rotation, the average value τ is 0 ($\int \tau = 0$). This means that the magnetorquers generate no useful work. Therefore, in the case of a solenoid ($\vec{\mu} = N \times I \times \vec{S}$), we must reverse the direction of the current every time $\sin(\theta(t)) = 0[\pi]$. For instance, if we need a positive magnetic moment to cancel the rotation:

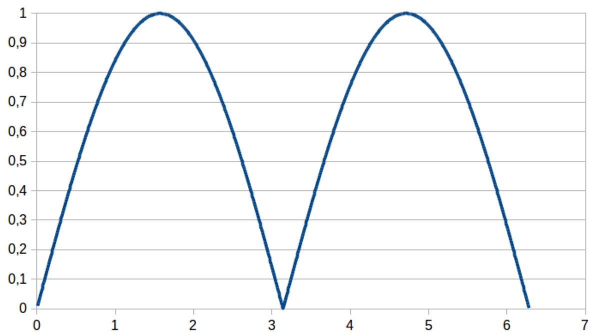

Figure 28: Norm of the torque over a full rotation, with I reversed when $\theta > \pi$

Furthermore, when the angle $(\widehat{\vec{\tau};\vec{B}})$ is small, the factor $\sin(\theta(t))$ is also small which means that the output torque is lower for the same power usage. For instance, if we put I=0 when $\sin(\theta(t)) < \frac{\sqrt{2}}{2}$, this is the resulting τ:

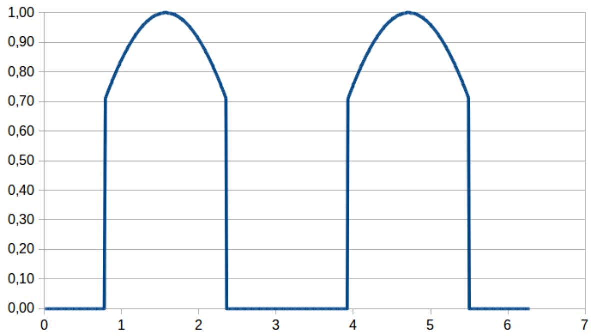

Figure 29: Norm of the torque over a full rotation, with a lower power usage

This particular example gives 86% of the magnetic moment output for 66% of the input power usage (compared to the previous plot), hence a better efficiency.

4.2.4 Solid mechanics

The fundamental formula describing the behavior of a solid subjected to a torque applied on a fixed axis is:

$$\Sigma\tau = J_\Delta \times \omega$$

Where τ is the torque (in $N \cdot m$), J_Δ is the moment of inertia and ω is the angular acceleration (in $rad \cdot s^{-2}$).

For any solid, the formula for J_Δ is:

$$J_\Delta = \iiint d(x,\Delta)^2 \rho dV$$

In the case of a cube whose side is a and mass is m with the fixed axis orthogonal to two of its sides and crossing the center of gravity, it is:

$$J_\Delta = \frac{1}{6} m a^2$$

Hence:

$$\omega(t) = \tau \times \frac{6}{ma^2}$$

The angular velocity (α, in $rad \cdot s^{-1}$) is simply the integral of the angular acceleration:

$$\alpha(t) = \int_t \omega(t) dt$$

In the case of our uniform cube:

$$\alpha(t) = \int_t \tau(\theta(t)) \times \frac{6}{ma^2} dt$$

When τ is relatively constant over time (when trying to correct a small angle misalignment for instance), the computations are easy.

However, in the case of high angular velocity (when trying to stabilize for instance), because our τ depend of the angle between two vectors that varies over time, and because the control algorithms will create even more variations over time, this expression is very hard to compute. Thankfully, it is periodic for the most part. In this case, we can use this approximation with a low error.

$$\alpha(t) = \int_t \frac{1}{2\pi} (\int_{\theta=0}^{2\pi} \tau(\theta) d\theta) \times \frac{6}{ma^2} dt$$

Finally, the rotation of the satellite around the axis is:

$$\theta(t) = \int_t \alpha(t) dt$$

The same technique can be applied on the three axis of rotation of the cube. Because the magnetorquers that generate the three torques are independent, the angular accelerations can be added together to obtain three dimensional angular acceleration, velocity and position of the satellite.