Investigation into precision sensors based on ultracold atoms

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UNIVERSITY OF BIRMINGHAM

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Contents

Abstract

Precision sensors based on ultracold atoms require control of external influences like the magnetic field. My research placement at the University of Birmingham's department of Physics and Astronomy was based on building an active magnetic field compensation system based on circuit developed in collaboration with École Normale Supérieure (ENS), Paris. This involved soldering electronic components onto a printed circuit board (PCB), building coils, testing functionality and taking measurements for characterization of the circuit.

Many people are familiar with magnets and the magnetic fields they produce, but not many people are familiar with how the magnetic systems behave at quantum level. Studying the behaviour of magnetic systems at quantum level will allow us to investigate the fundamental nature of magnetic systems in a very controlled way. It will also help produce extremely sensitive magnetometers which could be used in archaeological or resource-finding applications. We might even be able to explore new magnetic materials, which could change how data is stored as well as test the theoretical predictions for this unique system.

Introduction

Scientists know how the magnets work in the normal conditions, but what they don't know is how they behave at quantum level.

We know that magnetic fields are a vector quantity. In theory, this means that we can create a region of zero magnetic fields by superimposing of magnetic fields of equal magnitude from opposite directions[i].

This can be understood from the figure (1)[ii]. The magnetic field from the two south poles and the two north poles is cancelled in the centre, creating a region of no magnetic field. However, in practice the region will still have some residual magnetic field. The residual magnetic field won't actually be a physical limitation, but just noise of imperfect cancellation and the magnetic field will be reduced greatly in the targeted region.

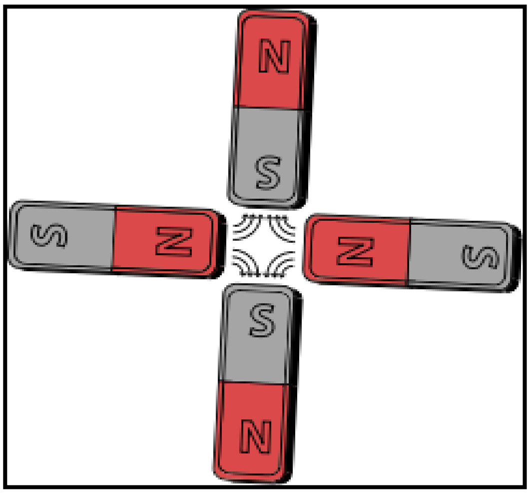

Figure 1: Obliteration of magnetic field in the centre of four magnets.

The project I undertook will help researchers see how the magnetic systems behave at a quantum level. To achieve this goal, we will first use optical cooling and trapping techniques to cool a cloud of alkali atoms in an ultrahigh vacuum chamber to temperature near absolute zero, using a specialised laser. At this low temperature, the atoms will condense and become a Bose-Einstein Condensate (BEC). A Bose-Einstein Condensate containing a few million atoms acts like a single quantum object and it is large enough to be seen on a camera. The Bose-Einstein Condensate will be held in an optical lattice in a very low magnetic field, so we can observe atoms interacting with each other, rather than the external magnetic field.

To be able to observe the behaviour of the atoms without the influence of external magnetic field, we will need a really low magnetic field. The best way to reduce the magnetic field is by active and passive shielding. Active shielding employs a set of coils, which oppose a portion of the magnetic field. This kind of shielding requires a sensor, which will sense the background magnetic field, and a feedback signal will be produced to oppose the field present. Passive shielding, on the other hand, refers to placement of µ-metal shields around the equipment. µ-metal shields are notable for their high magnetic permeability. They are an alloy of nickel and iron[iii]. My task was to work on active shielding for the magnetic compensation system.

Aims & Objectives

The aim of the research project is to create a magnetic field compensation system, which will control the external influences like the background magnetic field in the lab, on the Bose-Einstein condensate.

The main aim was to reduce the background magnetic field (0.5 Gauss) by around 8 orders of magnitude (so reduced to 50 nano-gauss). This will make the atom-atom magnetic interactions to start dominating the behaviour of the Bose-Einstein condensate.

This massive reduction in magnetic field from 0.5 gauss to 50 nano-gauss is intended to be achieved using a combination of both passive and active shielding.

The active shielding will provide the initial 2 or 3 orders of magnitude reduction, and then the passive shielding will provide the rest of 7 and 10 orders of magnitude of reduction. By using both passive and active shielding together, we can hopefully have benefits of both: a large reduction of DC and high frequency AC fields from the passive shielding as well as the low frequency AC and transient field suppression offered by active shielding.

Methods and Materials

Magnetic sensor board:

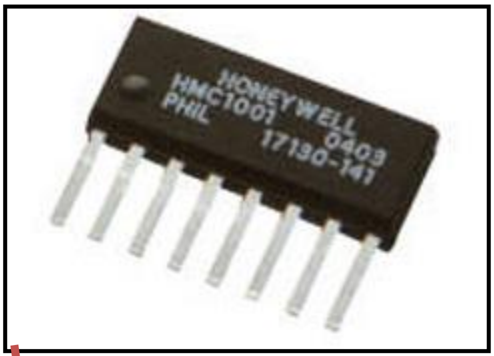

Figure 2: Honeywell HMC1001 1-axis sensor chip (4mm x 11mm)

One of the main parts of the magnetic compensation system is the sensor board, which can accurately measure the direction and magnitude of the magnetic fields. The magnetic sensor board is based on the Honeywell HMC1001 1-axis magnetic sensor, as they are ideal sensors for our purpose (figure 2)[iv].

The sensor requires some sort of control, hence why it was soldered onto an already designed printed circuit board, along with some resistors and capacitors.

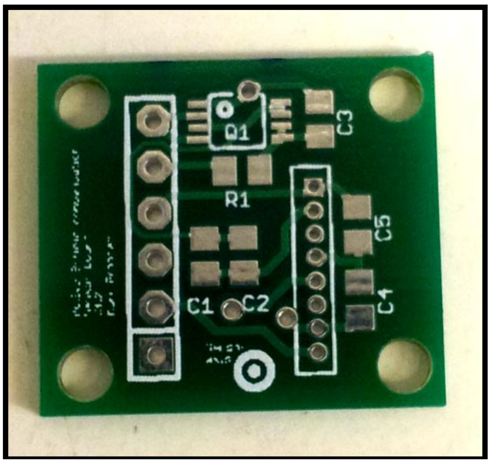

Figure 3: the sensor board with none of the components soldered onto it.

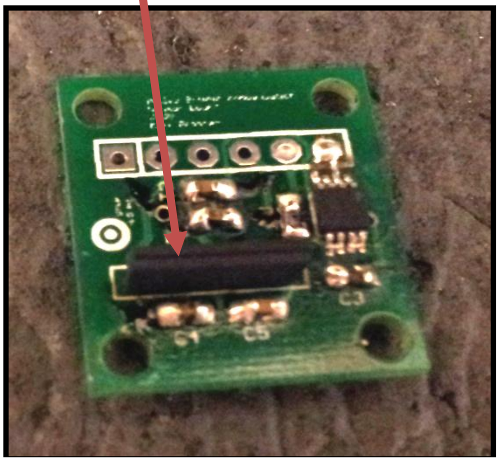

Figure 4: the sensor board with all the components soldered onto it.

The internal workings of a Honeywell sensor is shown in figure 5. Each section of the Permalloy strips is a resistor forming a Wheatstone bridge. The arrows on the strips indicate the direction at which the strips are magnetised. The sensor has some resistance, which changes as the magnetic field changes.

When a magnetic field is applied along the marked sensitive axis, the top left & right elements of the sensor will curl upwards in order to align and anti-align, respectively, their magnetic domain with the applied field. A similar process happens to the bottom two elements of the bridge as well.

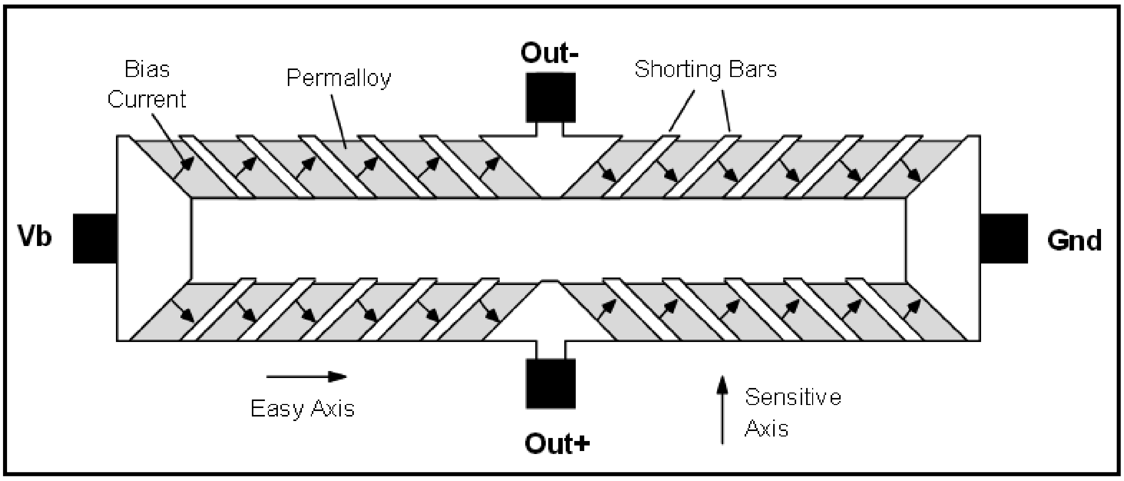

Figure 5: Honeywell sensor operating principle.

The magnetisation the Permalloy strips degrades over time and the strips gain a series of domains with random magnetisations. This is demonstrated by figure 6[v].

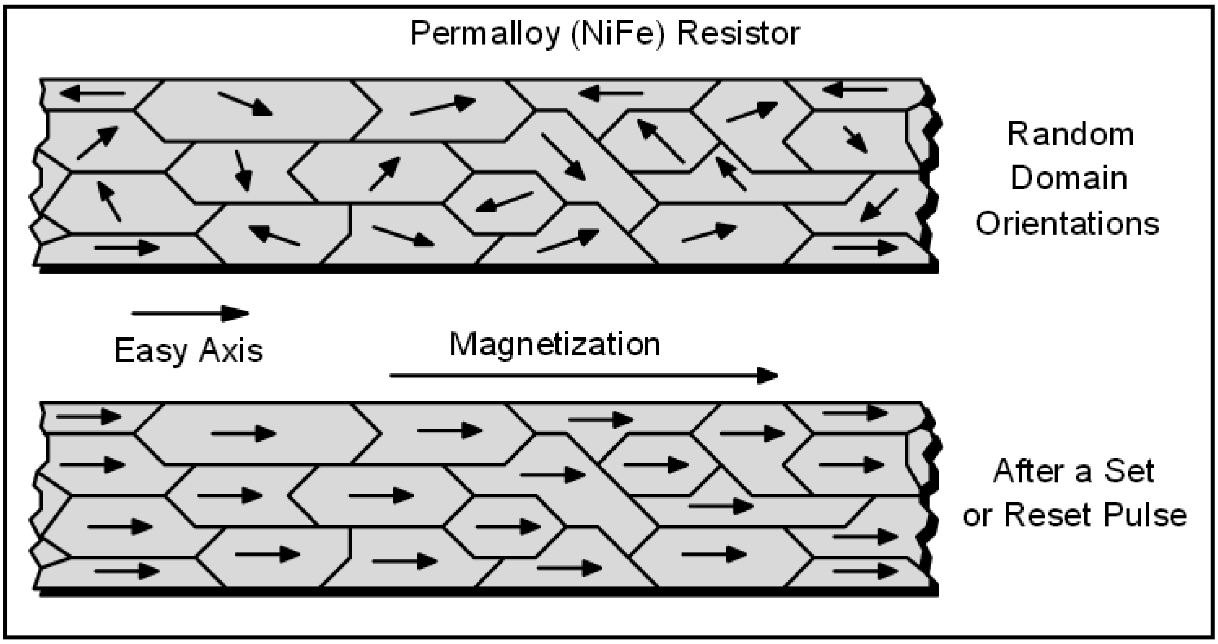

Figure 6: Sensor set/reset principle

The Permalloy strips' gaining a series of domains with random magnetisation reduces the response of the sensors and increases the noise. This doesn't cause much of a problem with our sensor, as the sensor comes with some built-in noise reduction feature in the form of a small coil around the die within the chip. When the chip is pulsed with a high current, it will re-magnetise the Permalloy strips to their default settings; hence magnetically renewing the sensor and regaining the high sensitivity.

A current pulse which causes the magnetisations of the strips to point in their factory-oriented directions is called a 'set' pulse, and one which anti-aligns them with their factory setting is called a 'reset' pulse (see figure 6).

After the sensor and the other components were soldered onto the printed circuit board, a wire and a plug were also soldered to the sensor board, in order to connect the sensor board to the main circuit board (see figure 7 & 8).

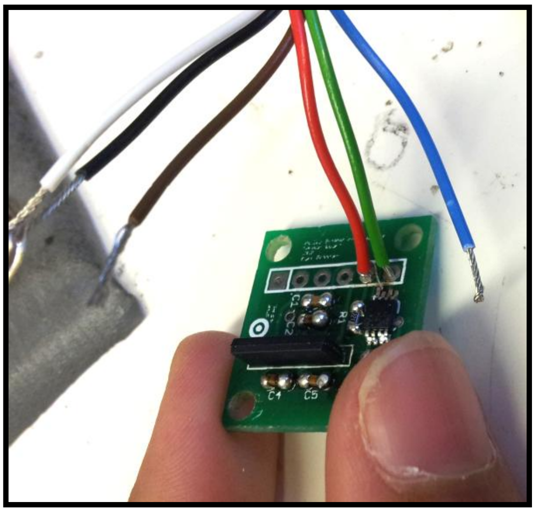

Figure 7: Wire being soldered onto the sensor board, after all the smaller components have been soldered.

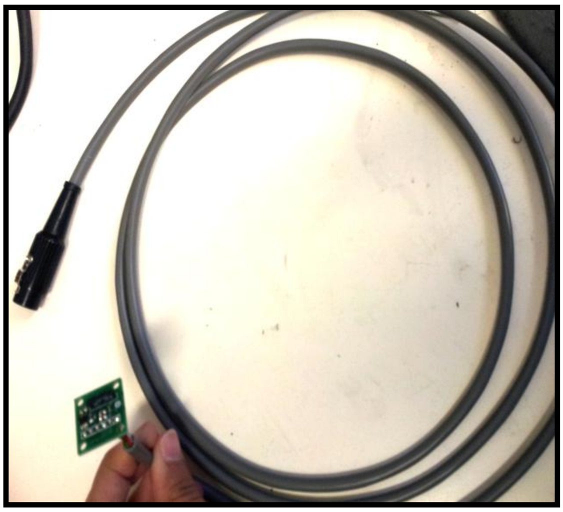

Figure 8: A fully assembled sensor board, with plug and wire attached.

The sensitivity of the Honeywell HMC1001 sensor depends on the supply voltage. In our case, it was 3.2mV/V/G x 10V (supply voltage), making the sensitivity at sensor output 32 mV/G. This sensitivity will be further amplified by the amplifier from the circuit by 1000 times, giving effective sensitivity of 32 V/G at the output of the amplifier. To test if the sensor works, I will be testing functionality by putting a magnet at different distances to the sensor, and recording what the sensor output is. If the sensor works, the sensor output will be different at different distances.

Main board:

The main function for the circuit board is to amplify the signal it receives from the sensor. Digital potentiometers are used in order to control the zero offset of the sensor, allowing us to control the field we wish to stabilise to i.e. maybe not to zero field, but some other field.

Building the main board involved soldering various components onto a printed circuit board (PCB).

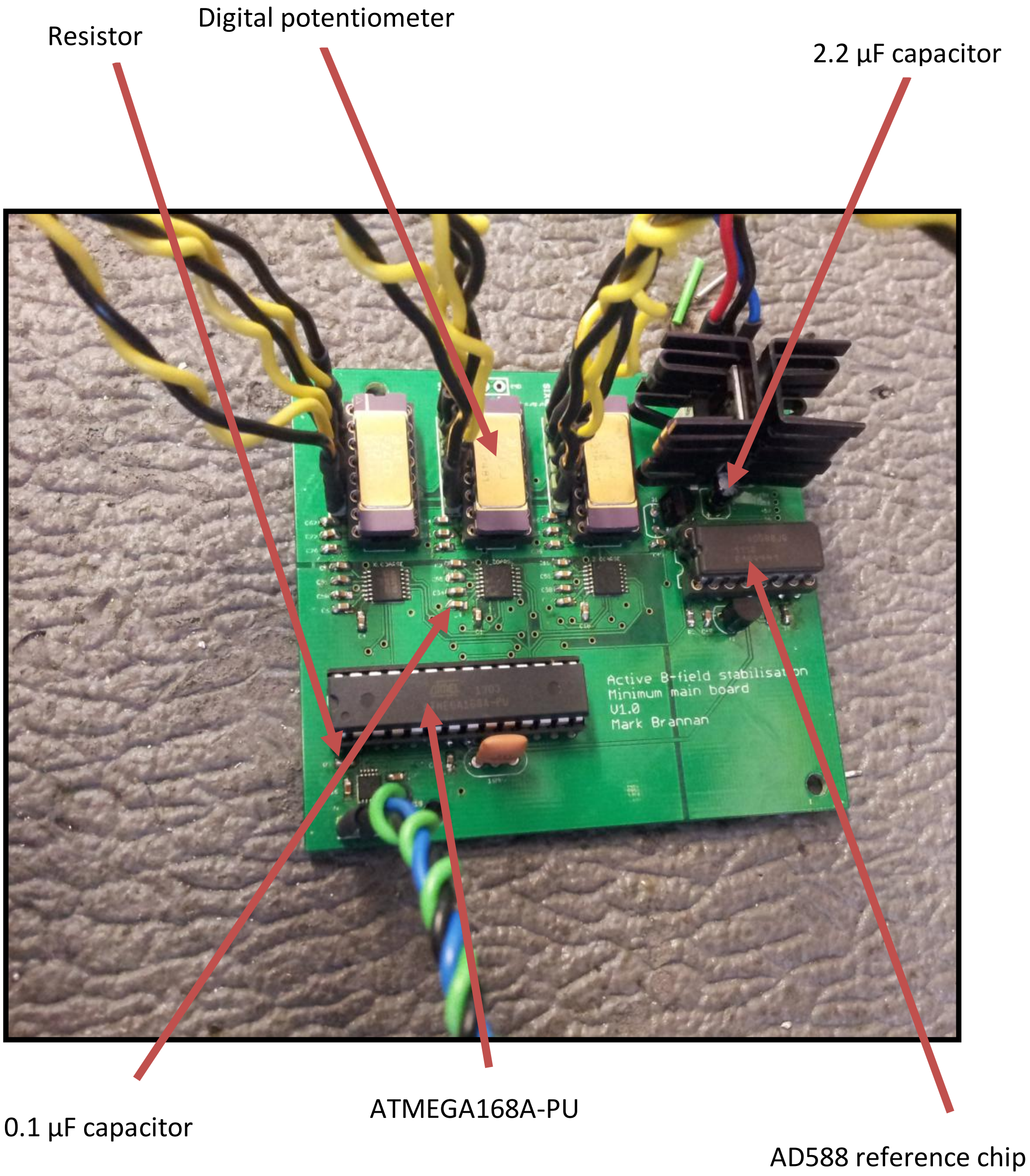

Figure 9: Main board, with the components soldered onto it.

Coils

In the introduction, we mentioned cancellation of a magnetic field using four magnets of equal magnitudes. Although, it is correct theoretically, it cannot be used in practice as that arrangement provides no control and adjustment.

Instead of the magnets, we used a pair of identical circular magnetic coils to produce a region of nearly uniform magnetic field. The coils were placed symmetrically one on each side of the experimental area along a common axis, separated by a fixed distance, which is equal to the radius of the coils. Each coil carries an equal electrical current flowing in the same direction. This arrangement is called 'the Helmholtz configuration'.

The current flow in the coils generates a magnetic field. This is because when you wind a wire, it can be used as an electromagnet; and as the number of turns increase on the wire, the magnetic field also increases. By increasing the current through the wires, we increase the field generated by the coils, and use this to cancel the field between them. The field generated by coils is in opposite direction to the magnetic field which we want to cancel. As the magnetic field is a vector, we can get it to be zero by applying current from opposite directions.

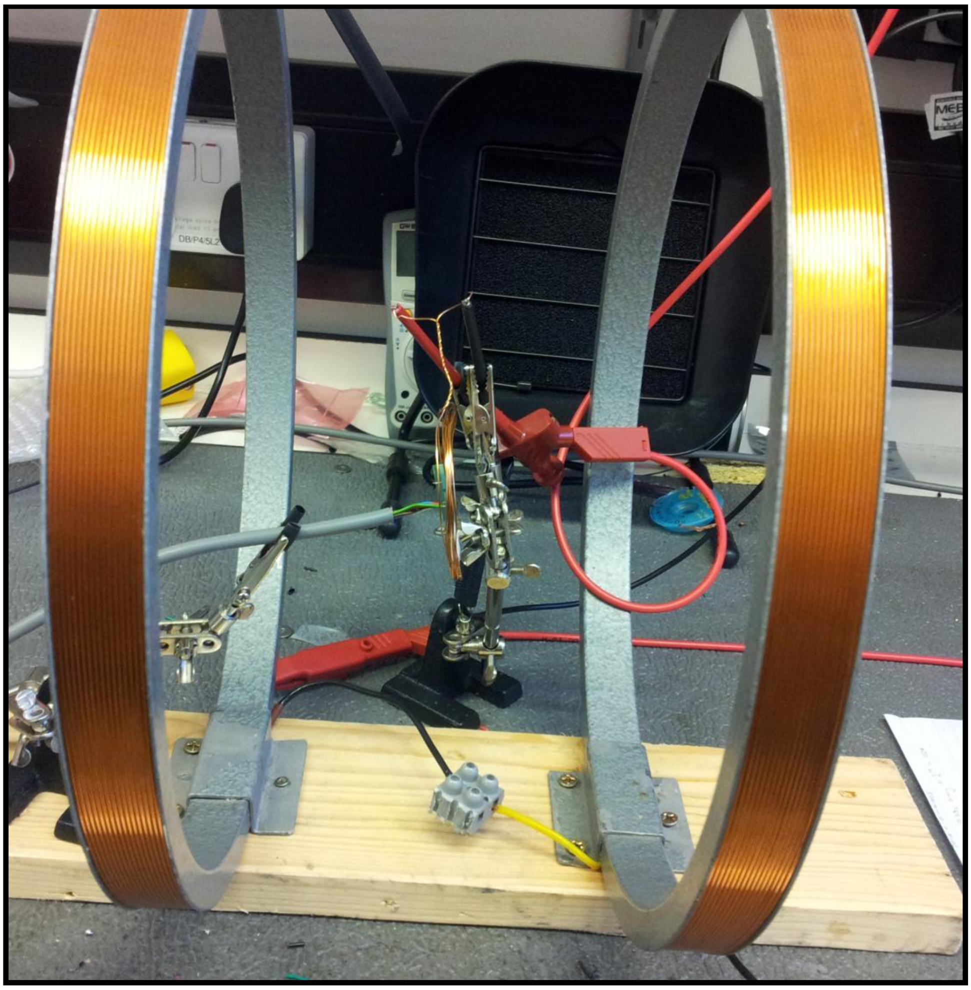

Figure 10: Helmholtz coils used in active shielding in our project

PID Circuit:

PID stands for Proportional, Integral, & Derivative. PID circuit is the device which controls and adjusts the current sent to the coils. The proportional part of the PID is the one which causes the most change, and the Derivative part is the one which is the most sensitive.

The function of the PID controller can be best understood by the example of fixing the temperature of water to a certain setpoint. Let’s say the set point is 22°C, and we want the heating and cooling process to reach a steady temperature as close to 22°C as possible. The PID circuit looks at the temperature of water, and sees how close it is to 22°C. If the temperature of water is already at 22°C, then the PID has to do nothing and it just sets its output to zero. However, if there is a difference, the PID heats or cools the water down, depending on what temperature it is at. The PID will keep adjusting till it has reached a steady temperature as close to 22°C as possible[vi].

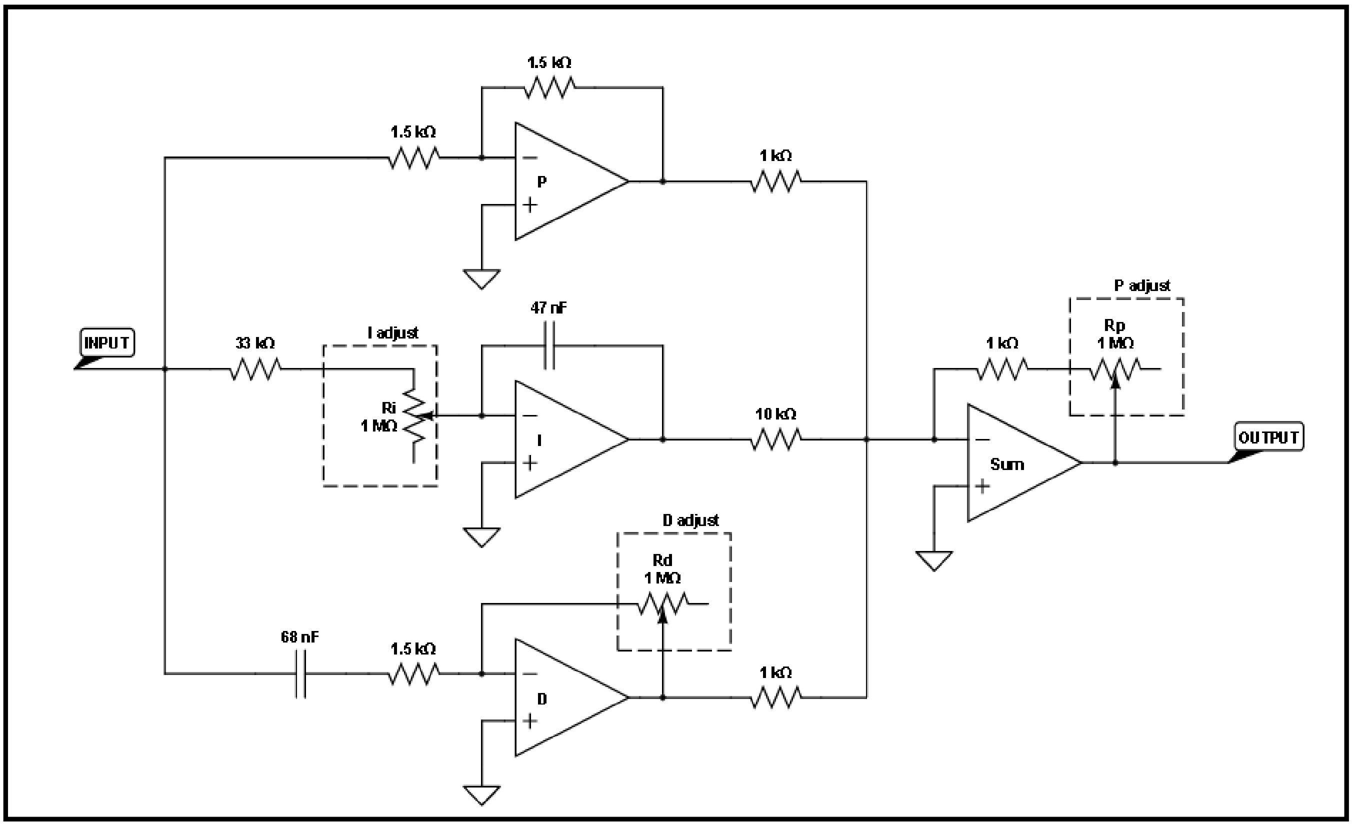

Figure 11: A schematic diagram of the PID circuit implemented in the current configuration of the active B-field control system.

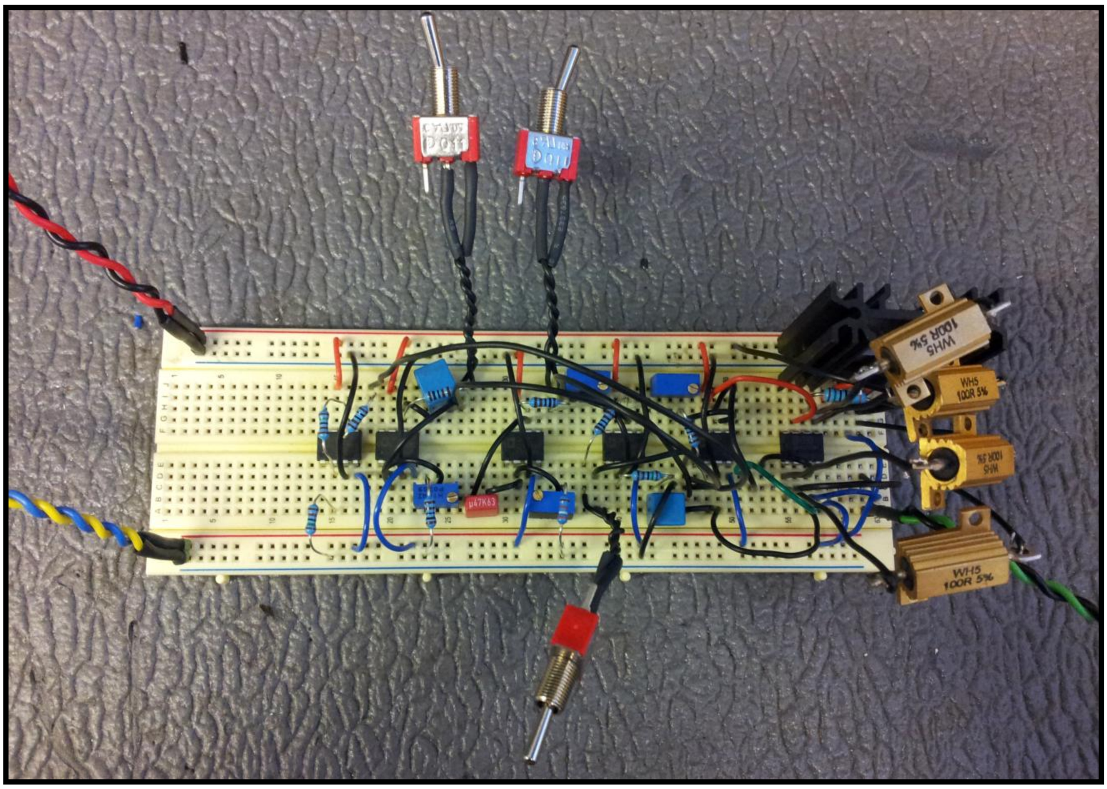

Figure 12: the PID circuit we used in our project to control and adjust the current sent to the coils.

Results (Tables, Figures, Graphs etc)

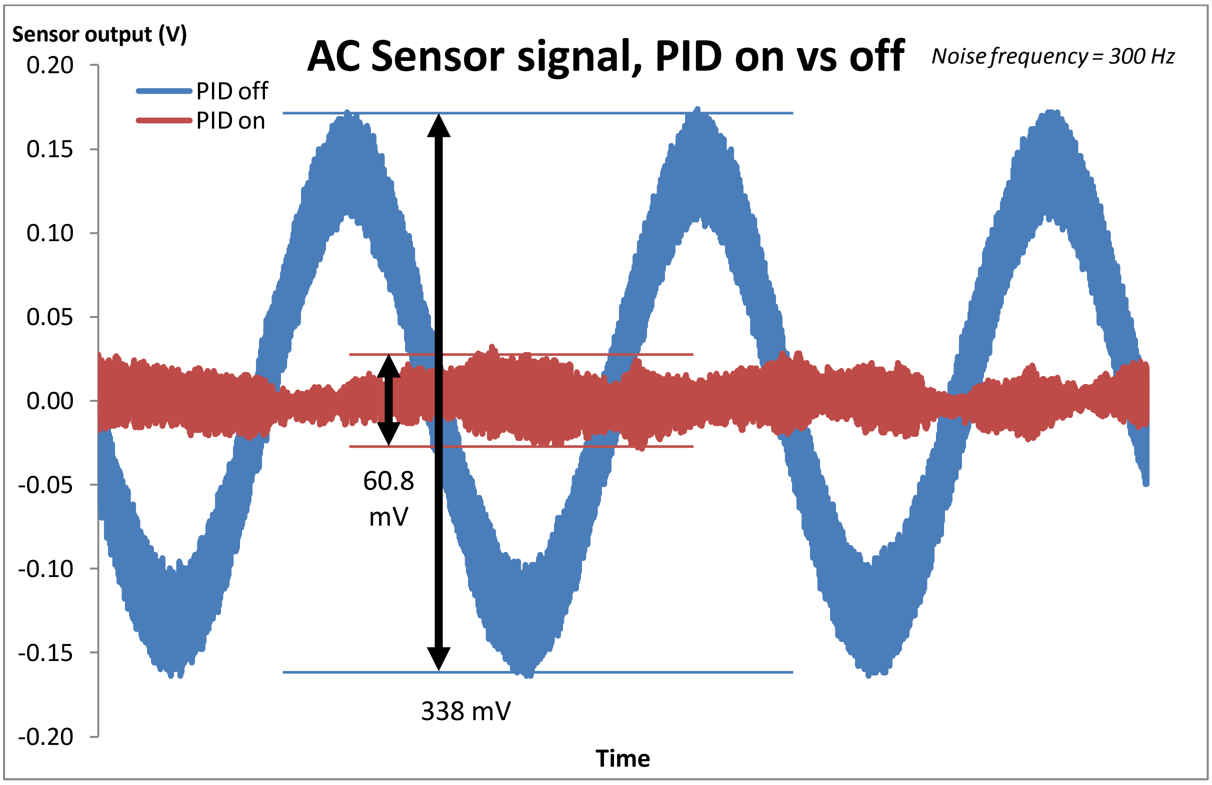

Figure 13: AC sensor signal, PID On vs. PID off

The AC sensor signal with the PID on is significantly reduced, as compared to the signal with PID off. The reduced signal is more stable as well, which makes it suited for what we want to do.

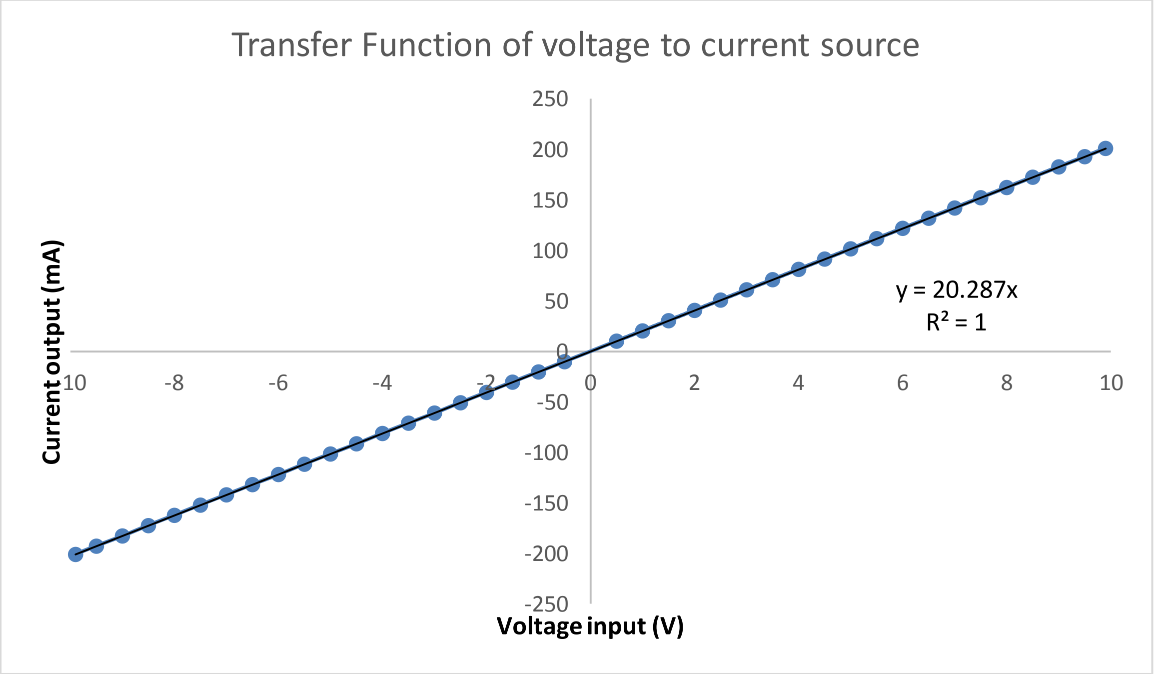

Figure 14: Transfer function of voltage to current source; a linear relationship can be seen between the two readings.

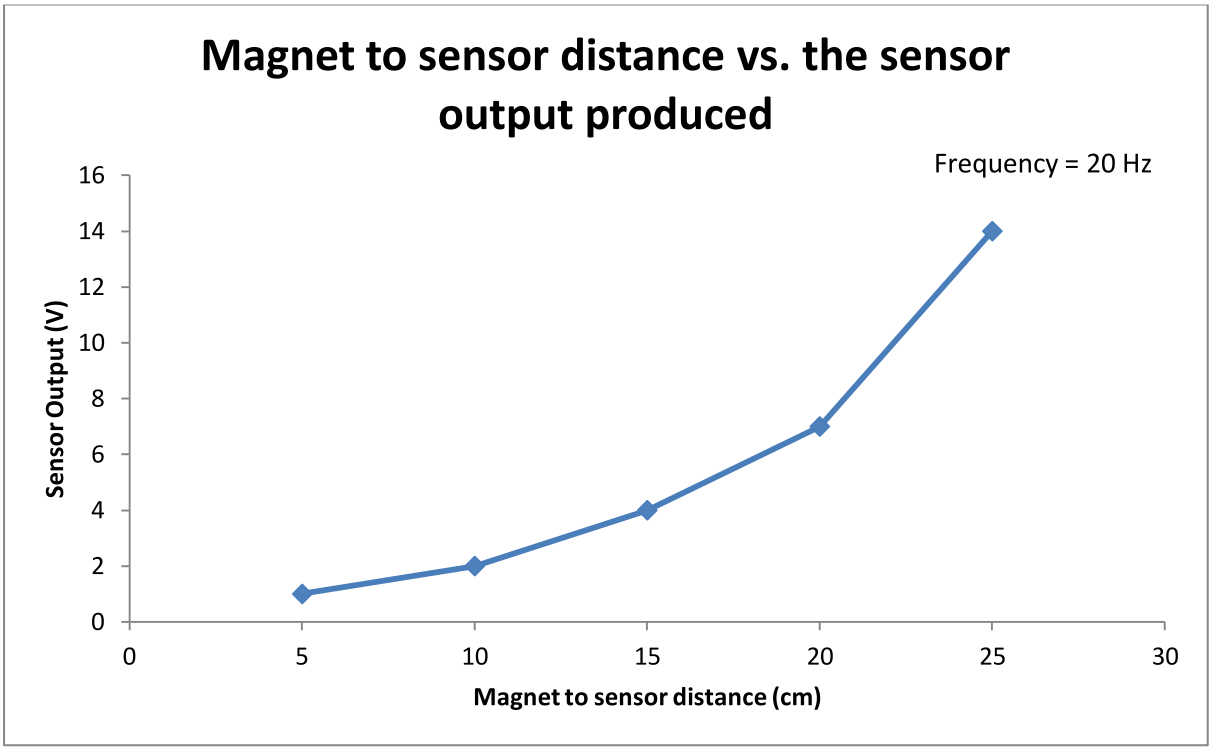

Figure 15: Magnet to sensor distance vs. the sensor output produced

The fact that the sensor output changes as the distance changes shows that the sensor functions properly.

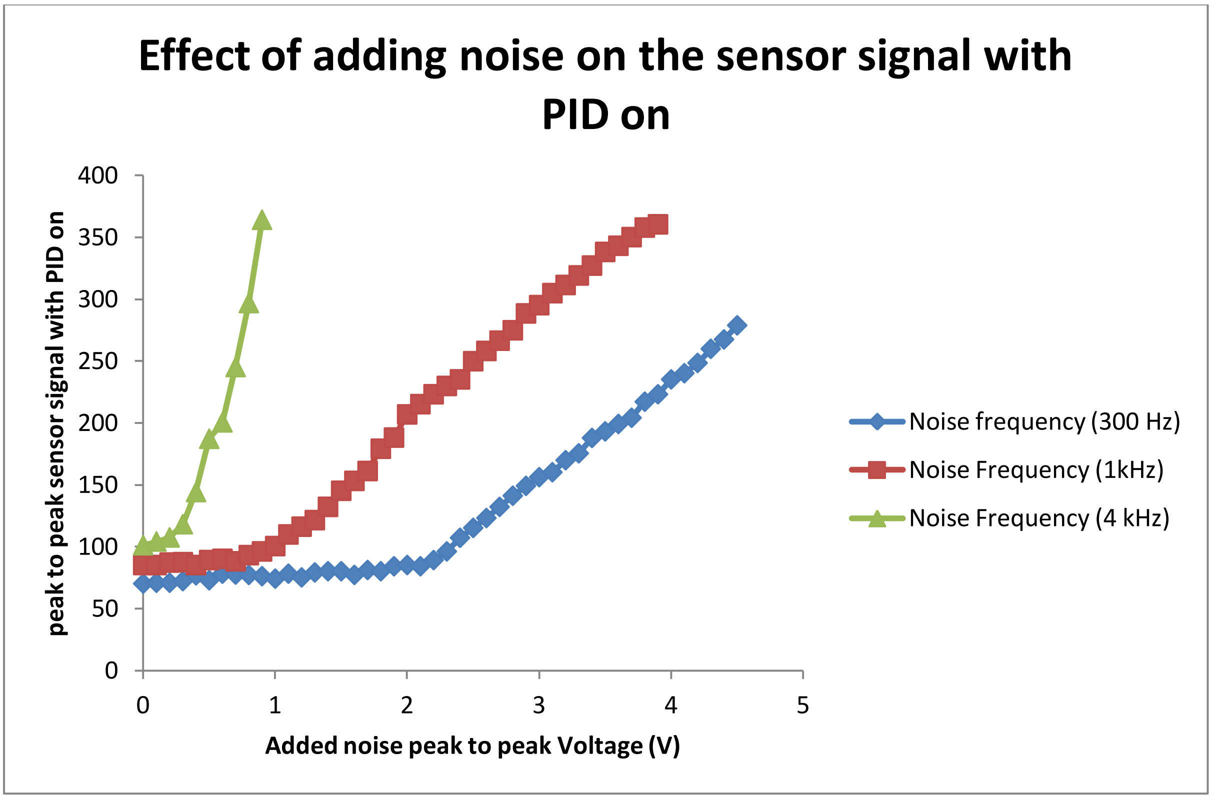

Figure 16: Effect of adding noise on the sensor signal with PID on. We can see that adding noise at higher frequency has more effect on the sensor signal.

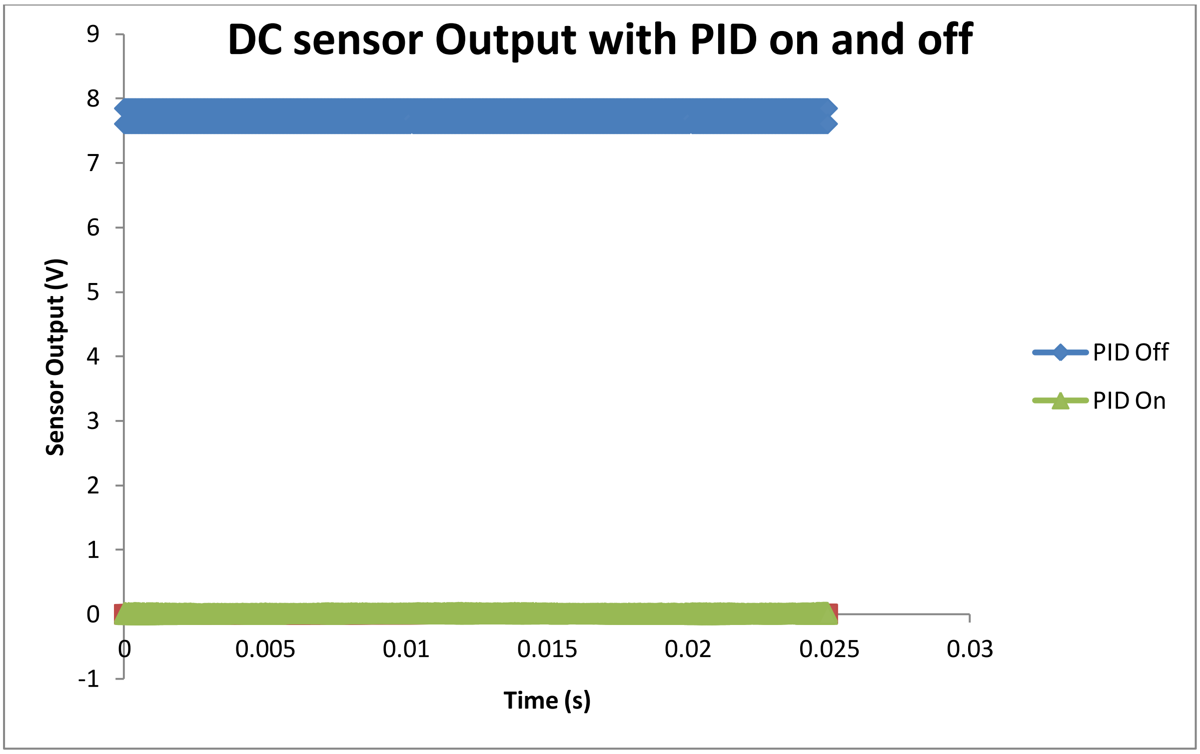

Figure 17: DC sensor output with PID On and off

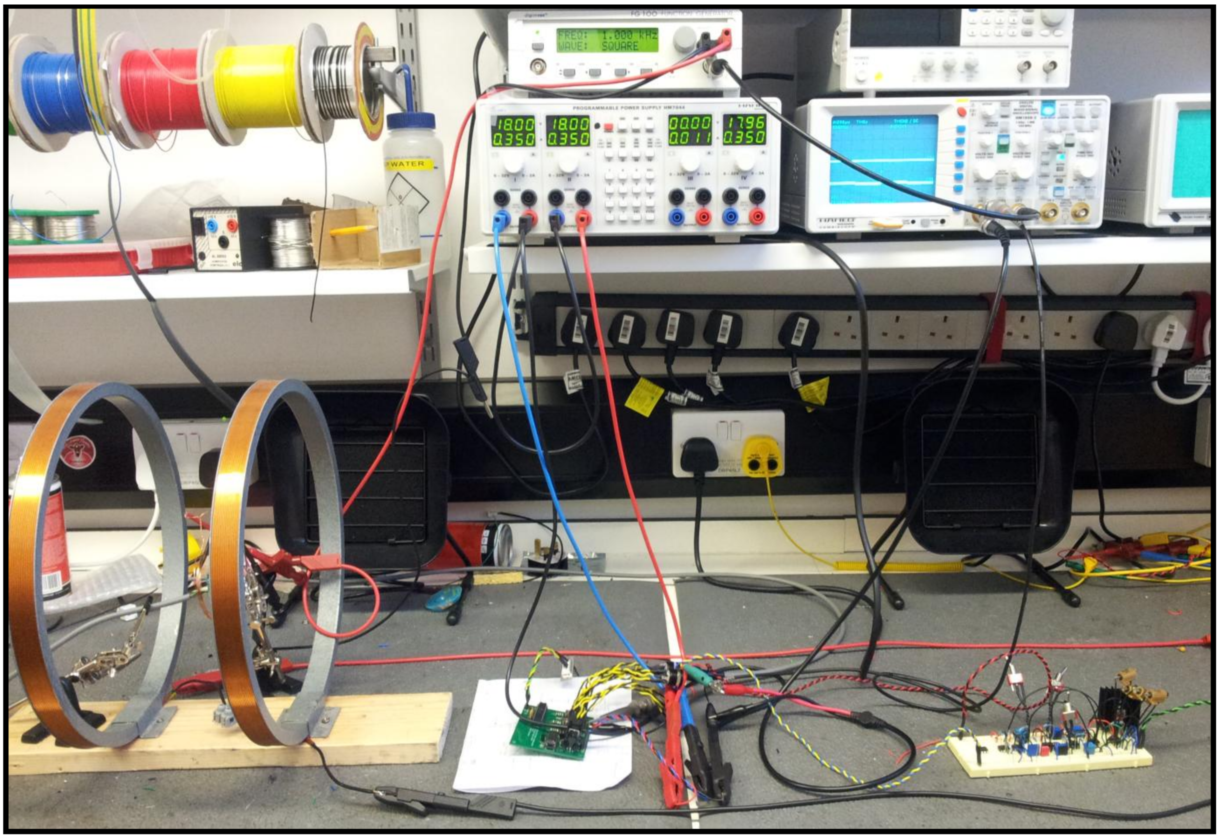

Figure 18: The complete set up for the magnetic compensation system including the PID circuit, the sensor board, the main board and the coils.

Discussion of Results

The active shielding system I built is to be used to stabilise the magnetic field within a given volume, where a cold atom experiment will be performed at an ultralow magnetic field. The active shielding system isn't expected to be good enough to get this ultralow field by itself, and as such passive shielding will be used as well – however, the active shield should be as good as possible.

A good enough active shielding system will be able to reduce fields as much as possible, both AC and DC, and be as stable as possible; so our system should be very insensitive to the magnetic noise at both AC and DC.

The insensitivity to the DC noise can be seen from figure 17, which shows how when the PID is on, the system reduces the DC field from some arbitrary field to zero, with a very small offset. When the PID is on, the field is much more reduced as the system compensates the field to zero, with very little offset.

The effect of the system on AC fields can be seen from figure 13. Figure 13 shows the AC sensor signal with PID on and PID off. It can be seen that the signal is much reduced and stays reduced over time when the PID is on, compared with the signal for when PID is off. This shows that the system is stable when PID is on. There still is some fluctuation present; that is the white noise spectrum we are left with, and it is probably due to the circuit itself. The white noise is present in all electronics, and an example of that would be when a television is tuned properly, and we get a black and white 'snow' picture.

Figure 16 shows how stable the system is to external noise. The graph in figure 16 shows a comparison between peak-to-peak PID locked signal vs. the amplitude of the noise signal we applied. We see from the graph that at faster frequencies, the system becomes unstable quicker than it does at lower frequencies. So this would mean that the system would be stable for a larger range, if it is working at lower frequencies.

For the PID circuit, we built our own current output source in the PID circuit. To check the functionality, some voltage was applied to the PID, and the current given out was recorded. The result of this test is shown on figure 14. The graph shows a linear relationship, with R^2=1, which shows that the fit we have done to data is a perfect fit. This means that the current source functions as we expect it to, and gives out the amount of current we want it to give out.

Figure 15 shows the relationship between the magnet-to-sensor distances against the sensor output produced. As the distance between the magnet and the sensor increases, so does the sensor output. This shows that the magnet is working properly, and tells us what the field looks like from the magnet.

Conclusion

We can conclude that the active magnetic field compensation works very well, as the PID system was stable to noise fluctuations during testing of functionality, for up to 5 times the typical background for 300 Hz, and it would probably be even better at lower frequencies. This is almost certainly covers any additional noise sources we might see in the lab.

The graphs from figure 13 and 17 show that the system most certainly stabilises and reduced the fields, which was our aim for this research. But does it provide 3 orders of magnitude in shielding, as we hoped at the start? Well, the signal we get from the sensor when the PID is off is 5 V, whereas the signal when PID is on is stable at 10 mV. This is 2 orders of magnitude. But if when we increased the noise signal so the uncompensated signal was 10 V, the PID on signal remain at 10 mV; this gives us our 3 orders of magnitude. This shows that the system can reduce to a certain amount of field, and the amount of reduction just depends on the external field that is there.

The current output from the PID is also like we expect it to be, and there is a relationship between the voltage given to the current source, and the current given out.

We know our sensor definitely works, because putting the magnet at different distances to the sensor, gave us different values for the sensor output; a clear indication of a functioning sensor (figure 15).

The optimum condition for the system to work would be at low frequencies, when the range during which the system is stable is the greatest, as seen on figure 16. This would mean that if we were to lower the frequency at which we test out equipment, we could get even more accurate and promising results from the equipment.

If i were to do a similar project again, I would think about using a more sensitive sensor, in order to improve the performance of the system. I would also think about using a less noisy PID circuit, so the fluctuations in the circuit are as low as possible.

The current source used for the PID was made by ourselves, but we could try using a better one, to optimise the performance. We also want lower resistance, higher inductance coils which will make the coils faster. We can make these faster coils by winding a coil ourselves, but having less turns in the wire, as more turns means higher inductance.

Another idea for improvement could be that we put our main circuit into a metal enclosure, which would act like a faraday cage. This would shield the circuit from electrical noise.

Acknowledgement

I would like to express my deep gratitude to my research supervisors Mark Brannan and Anna Kowalczyk for their constructive and valuable suggestions during the planning and development of this research work. I owe a great deal of this project’s success to Mark Brannan’s patient guidance and useful critique of this research work.

I would also like to extend my thanks to Professor Kai Bongs and Linda Rogers, without whom arranging this placement would not have been possible. I certainly learned a lot from my placement at the University of Birmingham, and am thankful to all the people who made that possible.

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[iv] Image source: http://www.acalbfi.com/be/p/0000001OHD

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