ELECTROMAGNETIC LEVITATION THESIS

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TERMS OF REFERENCE

The aim of this thesis was to investigate magnetic levitation and to design a working system capable of levitating an object from below. The system should be able to levitate an object from below, clear of an array of electromagnets without any form of support. There shouldn’t be any object, structure or device assisting in levitation, on the same level of elevation as the levitating object. The control and circuit complexities should be investigated and recommendations for improving the designed system should be made.

SUMMARY

Magnetic levitation is the process of levitating an object by exploiting magnetic fields. If the magnetic force of attraction is used, it is known as magnetic suspension. If magnetic repulsion is used, it is known as magnetic levitation.

In the past, magnetic levitation was attempted by using permanent magnets. Earnshaw’s theorem however, proves that this is mathematically impossible. There exists no arrangement of static magnets of charges that can stably levitate an object. There are however means of circumventing this theorem by altering its basic assumptions. The following conditions are exceptions to Earnshaw’s theorem:

- Diamagnetism: occurs in materials which have a relative permeability less than one. The result is that is eddy currents are induced in a diamagnetic material, it will repel magnetic flux.
- The Meissner Effect: occurs in superconductors. Superconductors have zero internal resistance. As such induced currents tend to persist, and as a result the magnetic field they cause will persist as well.
- Oscillation: when an A current is passed through an electromagnet, it behaves like a diamagnetic material.
- Rotation: employed by the Levitron, it uses gyroscopic motion to overcome levitation instability.
- Feedback: used in conjunction with electromagnets to dynamically adjust magnetic flux in order to maintain levitation.

Each of the above conditions provides solutions to the problem of magnetic levitation. The focus of this thesis is the feedback technique. Feedback with electromagnets can be divided into magnetic suspension and levitation.

Magnetic suspension works via the force of attraction between an electromagnet and some object. If the object gets too close to the electromagnet, the current in

the electromagnet must be reduced. If the object gets too far, the current to the electromagnet must be increased. Thus the information which must be sensed is the position of the levitating object. The position can then be used to determine how much current the electromagnet must receive. To prevent oscillations however, the rate of change of position must used as well. The position information can easily be differentiated to acquire the speed information required.

Electromagnetic levitation works via the magnetic force of repulsion. Using repulsion though makes a much more difficult control problem. The levitating object is now able to move in any direction, meaning that the control problem has shifted from one dimension to three. There is much interest in levitation due to its possible applications in high speed transport technology. These applications can be broadly referred to as MagLev, which stands for **mag**netic **lev**itation. A system which more closely resembles the work done in this thesis project is the “MagLev cradle”. The MagLev cradle is a system designed by Bill Beaty. It is able to levitate a small rod magnet for a few seconds at a time. This system suffers from serious instability. As such levitation can only be maintained for a few seconds.

The MagLev cradle utilizes an arrangement of up to 12 electromagnets and their control circuits in a “v” configuration to levitate a bar magnet. The MagLev cradle uses rapid switching circuits to control current to the electromagnets. If the bar magnet falls too close to the electromagnet, the circuit switches on, thus applying more repelling force. If the bar magnet rises too high above the electromagnet, it turns off, thus removing the repelling force.

The system developed for this thesis uses the position sensing technique employed by the magnetic cradle. Hall Effect sensors are placed on each of the electromagnets in the system. Each electromagnet and its current control circuitry operates as an independent system to levitate part of a bar magnet.
The Hall effect sensor is a device that senses magnetic flux. It is also capable of detecting the magnetic flux orientation. It is placed on an electromagnet to sense

the presence of the bar magnet we wish to levitate. The circuitry is configured such that is magnetic flux is detected; the system will energize the electromagnet in order to make the net magnetic flux with the hall effect sensor zero. Therefore this system electronically simulates the Meissner effect by repelling both north and south poles of a magnet. Experiments were also done to investigate various configurations of electromagnets in order to achieve stable magnetic levitation.

This current control circuit for the electromagnets used an opamp summer circuit and a power amplification stage (sink/source transistor circuit). Initial tests revealed that besides position sensing, speed information was required as well. This was achieved by adding a phase lead circuit, which negated the phase lag caused by the electromagnet (an inductive load) and the control circuitry.

Different configurations of electromagnets were used to attempt to levitate a bar magnet. The main problem that was soon identified was that of keeping the levitating bar magnet in the area above the electromagnets. Despite moving the electromagnets closer and further apart, the bar magnet could not be effectively trapped above the electromagnets. The bar magnet has a tendency to “slide” off the ends, as the end magnets cannot react quickly enough to movements in the bar magnet. Thus current system lacks the control circuitry required to achieve stable electromagnetic levitation.

At present, pairs of electromagnets can effectively levitate part of a bar magnet which is supported at one end. If the necessary control circuit required to effectively hold the levitating bar magnet in position above the electromagnet can be designed, then a working system can be quickly realised.

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SYMBOLS

mV/G: millivolts per Gauss

K: Kelvin

C: capacitance (farads)

A: area of capacitor plates (m^2)

ε_0: permittivity of free space

ε_r: relative permeability

1. INTRODUCTION TO MAGNETIC LEVITATION

Magnetic levitation is the process of levitating an object by exploiting magnetic fields. In other words, it is overcoming the gravitational force on an object by applying a counteracting magnetic field. Either the magnetic force of repulsion or attraction can be used. In the case of magnetic attraction, the experiment is known as magnetic suspension. Using magnetic repulsion, it becomes magnetic levitation.

In the past, magnetic levitation was attempted by using permanent magnets. Attempts were made to find the correct arrangement of permanent magnets to levitate another smaller magnet, or to suspend a magnet or some other object made of a ferrous material. It was however, mathematically proven by Earnshaw that a static arrangement of permanent magnets or charges could not stably magnetically levitate an object

Apart from permanent magnets, other ways to produce magnetic fields can also be used to perform levitation. One of these is an electrodynamic system, which exploits Lenz's law. When a magnet is moving relative to a conductor in close proximity, a current is induced within the conductor. This induced current will cause an opposing magnetic field. This opposing magnetic field can be used to levitate a magnet. This means of overcoming the restrictions identified by Earnshaw is referred to as oscillation.

Electrodynamic magnetic levitation also results from an effect observed in superconductors. This effect was observed by Meissner and is known as the Meissner effect. This is a special case of diamagnetism.

This thesis will mainly deal with electromagnetic levitation using feedback techniques to attain stable levitation of a bar magnet.

2. THE EARNSHAW THEOREM

Earnshaw’s theorem basically proves that a static magnet cannot be levitated by any arrangement of permanent magnets or charges. This can be simply proved as follows:

“The static force as a function of position ***F(x)*** acting on any body in vacuum due to gravitation, electrostatic and magnetostatic fields will always be divergenceless. $\mathrm{div}\mathbf{F} = 0$. At a point of equilibrium the force is zero. If the equilibrium is stable the force must point in towards the point of equilibrium on some small sphere around the point. However, by Gauss' theorem,

$$_S\int \mathbf{F}(\mathbf{x}).d\mathbf{S} = {}_V\int \mathrm{div}\mathbf{F}.\, dV$$

The integral of the radial component of the force over the surface must be equal to the integral of the divergence of the force over the volume inside which is zero.” – (Philip Gibbs and Andre Geim, March 1997)

This theorem though makes certain assumptions. Thus the result can be circumvented under certain conditions. The exceptions to Earnshaw’s theorem are as follows:

2.1 QUANTUM THEORY

Firstly this theorem only takes into account classical physics and not quantum mechanics. At the atomic level there is a type of levitation occurring through forces of repulsion between particles. This effect is so small however, that it is not generally considered as magnetic levitation.

2.2 ROTATION

This property is used in the patented magnetic levitation display called the Levitron. The Levitron uses an arrangement of static permanent magnets to levitate a smaller magnet. The system overcomes the instability described in Earnshaw’s theorem by rotating the levitating magnet at high speed.

2.3 DIAMAGNETISM

Earnshaw’s theorem doesn’t apply to diamagnetic materials, because they have a relative permeability less than one. This means that they don’t behave like regular magnets, as they will tend to repel any magnetic flux.

2.4 MEISSNER EFFECT

A special case of diamagnetism is observed in conductors cooled to below their critical temperature (typically close to 0 K). Below this temperature, they become superconductors, with an internal resistance of zero. They attain a relative permeability of zero, making them the perfect diamagnetic material. This allows them to maintain their repelling magnetic field as long as a foreign source of magnetic flux is present.

2.5 FEEDBACK SYSTEMS

The position of the levitating magnet can be sensed and used to control the field strength of an electromagnet. Thus the tendency for instability can be removed by constantly correcting the magnetic field strength of the electromagnets to keep a permanent magnet levitated.

2.6 OSCILLATION

Passing an alternating current through an electromagnet causes eddy currents to flow within its core. These currents according to Lenz's law will flow such that they repel a nearby magnetic field. Thus, it causes the electromagnet to behave like a diamagnetic material.

Ref: Philip Gibbs and Andre Geim, "*magnetic levitation*". , March 1997. [Online]
http://math.ucr.edu/home/baez/physics/General/Levitation/levitation.html ,
(October, 2005)

3. THE LEVITRON

The Levitron is a commercial toy that was invented by Roy Harrigan. It is a patented device that performs magnetic levitation with permanent magnets. It overcomes the limitation set by Earnshaw’s theorem through rotation.

The base consists of a carefully arranged set of permanent magnets. The object that is levitated is a circular permanent magnet inside a spinning top shape. Harrigan found that the instability described by Earnshaw could be overcome by having the levitating magnet spin at high speed. This gyroscopic motion provides a simple solution to the spatial instability problem defined by Earnshaw.

Harrigan was able to determine the speed above which the levitating magnet would have to spin in order to maintain stable levitation. If the angular speed was too slow, the gyroscopic stabilising effect would be lost. The spinning top shape for the levitating magnet was adopted in order to reduce the drag caused by air friction as the top spins. Thus it would be able to spin for longer.

He also found that as the top spins, a diamagnetic effect occurs. The motion of the spinning levitating top relative to the base magnets causes a current to be induced in the spinning top. The induced currents set up a magnetic field which opposes the base magnets in such a way that it tries to slow the rotation of the levitating top, causing the levitating time to be reduced. Thus the Levitron uses ceramic magnets and ceramic materials instead of conducting metals. This reduces the induced currents and thus the unwanted opposing magnetic fields. This allows the top to spin for longer.

Because the air friction and induced currents cannot be completely eliminated however, the levitating effect cannot be maintained or controlled.

Fig1: The Levitron top levitating above its permanent magnet base.

Image from: http://www.physics.ucla.edu/marty/levitron/

Ref: Martin D. Simon, Lee O. Heflinger 1997. “Spin stabilized magnetic levitation”, American Journal of Physics (April 1997)

4. THE MEISSNER EFFECT AND SUPERCONDUCTORS

One of the interesting properties of superconductors was researched by Meissner, and is known as the Meissner effect. The Meissner effect is a phenomenon that occurs when certain conductors are cooled below their critical temperature which is typically 0 K. It was observed that under this condition the conductor would become a superconductor, and would in fact repel magnetic fields of any orientation. In other words, a piece of superconducting material cooled to below its critical temperature will repel a magnetic south pole or a magnetic north pole, without having to move it. This is a special case of diamagnetism.

In a conventional conductor such as copper, if a magnet is brought in proximity to it, an electric current is induced in the copper. According to Lenz's law, this induced current will establish a magnetic field to counteract or oppose the nearby magnetic field caused by the magnet. Due to the fact that copper is not a perfect conductor however, the induced current quickly dies away due to the internal resistance present in the conductor. When the current disappears, the magnetic field collapses along with it. Thus, this induced current and its accompanying magnetic field are only observed when the nearby magnet is moving. The movement of the nearby magnetic field would then constantly stimulate the induced current and the opposing magnetic field. This phenomenon explains the damping effect that a copper plate in close proximity has on the movement of a magnet.

As can be seen from the above explanation, theoretically, if the induced current did not dissipate due to the resistance of the conductor, then the accompanying magnetic field should persist as well. This is in effect, what happens in a superconductor cooled to below its critical temperature. There is zero resistance inside the superconductor, and so the induced current and its accompanying magnetic field would not dissipate, even if the magnet stopped moving. As long as the magnet is present, the opposing magnetic field will exist. This causes a magnet brought close to a cooled superconductor to be repelled, regardless of which magnetic pole the superconductor is exposed to. The opposing magnetic field induced in a superconductor can become so strong that it can effectively match the downwards force on a nearby magnet caused by its weight. The resultant effect observed is that a magnet, placed above a cooled superconductor, can remain there, stably levitated.

This does not however explain how come the magnet remains stably levitated above the superconductor without “slipping” off the side. As Earnshaw showed, simple magnetic repulsion is not sufficient to maintain stable levitation. This problem is solved at the molecular level. Within the superconductor are impurities, i.e. areas which do not have electric current flowing in them, and as a result are not producing an opposing magnetic field. These areas, although small, are big enough to allow regions of the magnetic field from the nearby magnet to penetrate the superconductor. If the magnet moved, the magnetic field would have to move with it. But because the magnetic field is unable to penetrate the superconductor in any other area, the magnetic field is effectively locked in place. Thus, because the magnetic field is being held in place by the “holes” in the opposing magnetic field of the super conductor, the magnet too, is held in place. This is what holds the magnet in place above the superconductor and keeps it stably levitated. This is known as flux pinning.

Fig2: A magnet levitating above a superconductor

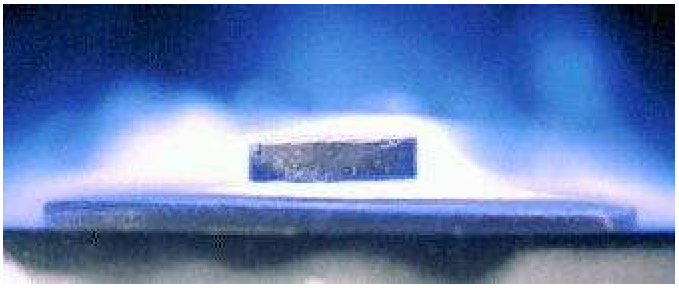


Image from: http://math.ucr.edu/home/baez/physics/General/Levitation/levitation.html

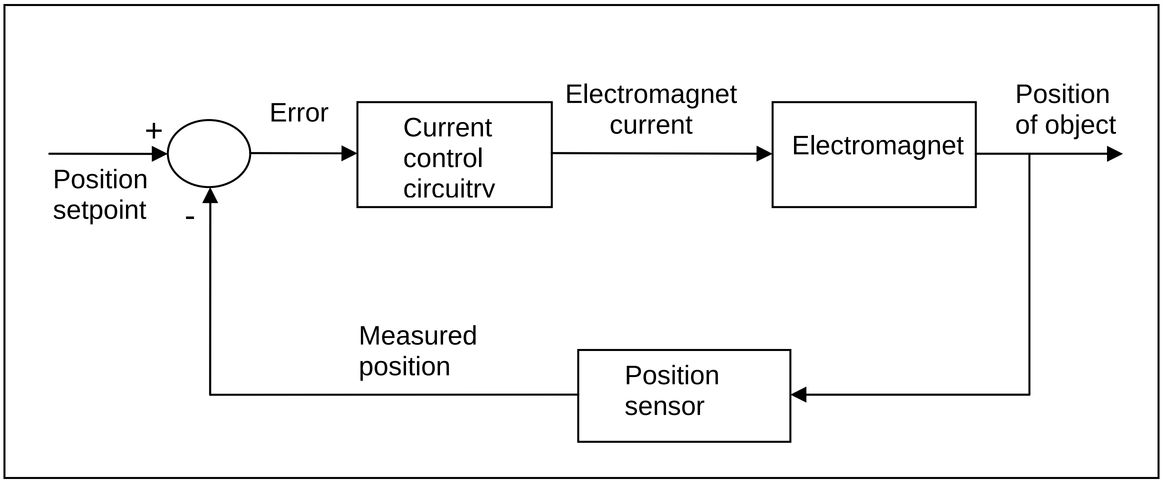
Ref: “The Meissner Effect” [online]
http://www.users.qwest.net/~csconductor/Experiment_Guide/Meissner%20Effect.htm
(October 2005)

5. ELECTROMAGNETIC MAGNETIC SUSPENSION

The easiest way to levitate an object electromagnetically (from a control perspective) is via magnetic suspension. The object that is to be levitated is placed below an electromagnet (only one is required), and the strength of the magnetic field produced by the electromagnet is controlled to exactly cancel out the downward force on the object caused by its weight. This method circumvents Earnshaw's theorem by making use of feedback.

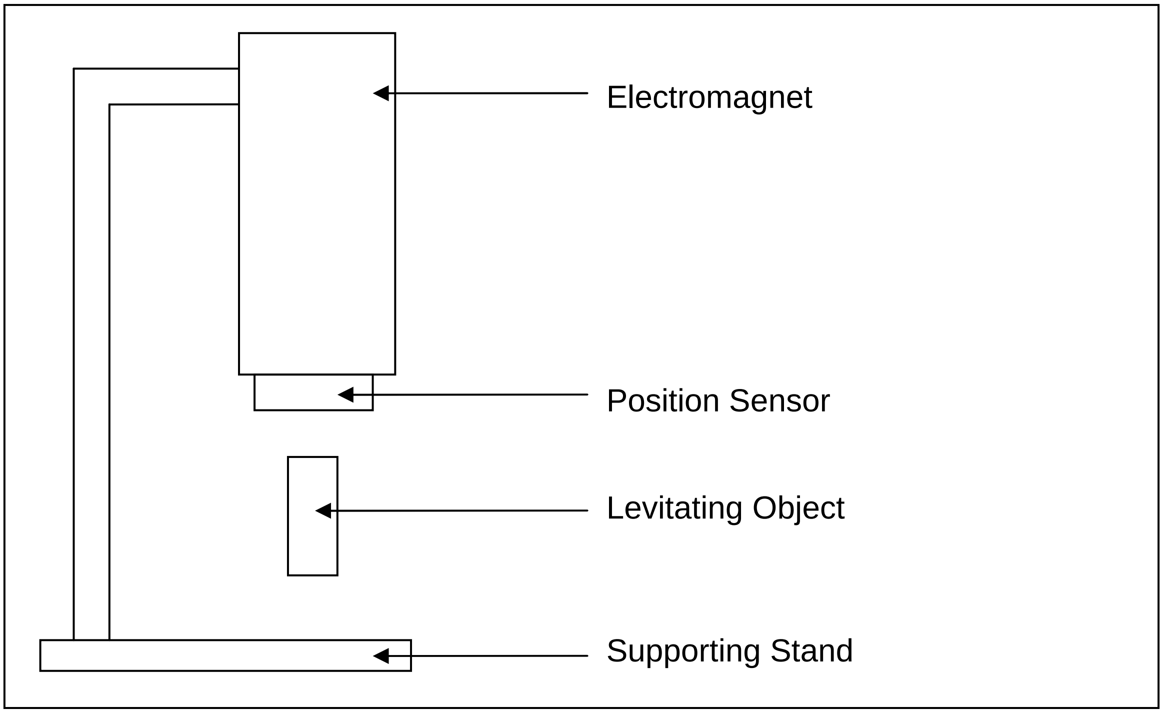
Thus the system only has to contend with one force, the levitating object's weight. This system works via the force of attraction between the electromagnet and the object. Because of this, the levitating object does not need to be a magnet; it can be any ferrous material. This further simplifies the design considerations. To prevent the object from immediately attaching itself to the electromagnet, the object's position has to be sensed and this information fed back into the control circuit regulating the current in the electromagnet. This produces the basic feedback arrangement depicted below.

Fig3: Diagram showing the basic control arrangement of a magnetic suspension system.



If the object gets too close to the electromagnet, the current in the electromagnet must be reduced. If the object gets too far, the current to the electromagnet must be increased. A possible physical arrangement is shown below.

Fig4: Diagram showing the physical model of a magnetic suspension system.



There are various ways to sense the position of the levitating object. One way is optically. A beam of light is shone across the bottom of the electromagnet and detected at the other side. As the object obscures more and more light (indicating that the object is getting closer to the electromagnet) the electromagnet controller limits the current more and more. As the object drops away from the electromagnet, more light is exposed to the sensor, and the current to the electromagnet is increased. This system can prove difficult to properly set up, as the alignment of the light source and the light sensor is critical. Also critical is the shape of the levitating object, because the rate at which light is obscured or exposed should be linear as the object rises and falls. This will produce the best results.

The position can also be sensed capacitively. A small metal plate can be placed between the levitating object and the electromagnet. The capacitance between the levitating object and the metal plate can be sensed and used to determine the distance between the two. The advantage of this system is that the capacitance between the plate and the object is always linear regardless of the shape of the levitating object. The capacitance is given by the following equation.

$$C = \frac{A\varepsilon_0\varepsilon_r}{d}$$

C = capacitance (farads)
A = area of capacitor plates (m^2)
ε_0 = permittivity of free space
ε_r = relative permeability
d = distance between plates (m)

The metal plate positioning is also not as critical as the sensor positioning in the optical solution, and is thus slightly easier to set up. The disadvantage of this solution is that the metal plate placed below the electromagnet may have undesired effects on the magnetic behaviour of the system. If the material is ferrous, its proximity to the electromagnet and its shape would alter the resultant magnetic field shape in the area of the levitating object. Also the circuitry required to sense the capacitance accurately is fairly complex and sensitive to circuit layouts.

Another means of position sensing is via ultra sonic sound transmitters. These work on the concept of sonar. A chirp sound signal is transmitted and the time taken for the signal to return after bouncing off the levitating object is used to determine its distance. This however, is a very complex solution given the simplicity of the system? Also because of the very short distance over which the ultrasonic sensors would have to transmit, this solution becomes unfeasible.

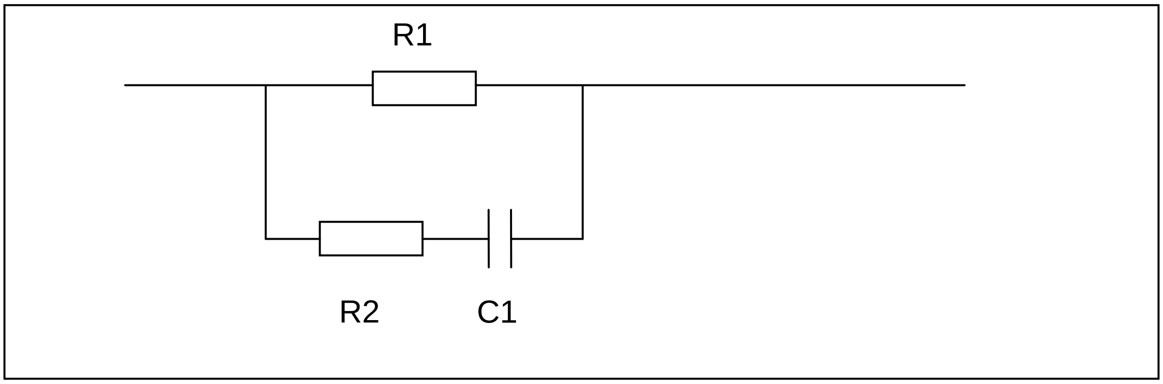
The position can also be sensed with a Hall Effect sensor. For this solution, one hall sensor can be placed on the north pole of the electromagnet, and the other on the south pole. The hall sensor is a device which has a linearly increasing voltage response to an increasing magnetic flux. It can detect both north poles and south poles, by either raising its output voltage above its quiescent output voltage, or decreasing its output voltage below its quiescent output voltage. The outputs of both sensors can be sent to the inputs of a differential opamp in order determine the difference between them.

When there is no object to levitate, the outputs of both sensors will be equal. As an object approaches the bottom of the electromagnet however, it becomes magnetized by the magnetic field of the electromagnet. Thus, there would exist two magnetic fields on either side of the hall sensor on the bottom of the electromagnet. One would be due to the electromagnet and the other due to the magnetizing field in the levitating object. This would cause the bottom hall sensor to detect the net magnetic field, while the top hall sensor would still be detecting the magnetic field of the electromagnet only. The differential opamp would then output a signal which could be used to control the current to the electromagnet. Because the hall sensors have a linear response, the differential opamp output would rise and fall linearly as the object rose and fell.

The circuit used to implement a solution of this nature only has to achieve linear current control from 0 amperes to the maximum operating current. Only a single supply is required, along with the sensor circuitry and the proper gain to the current source control. It has been noted however in experiments with this system, that oscillations in the levitating object exist due to the phase lag caused by the current control circuitry and the electromagnet itself, which is in fact a large inductive load. In physical terms, the problem is that the circuit reacts too slowly to the changes in position of the levitating object. If the object drops it is inherently accelerating. The control circuit would over compensate with a large correcting current, and by the time it slacked off, the object would be accelerating towards the electromagnet. This causes growing oscillations as the control circuitry constantly over compensates until eventually levitation cannot be maintained and the object falls.

Thus to counteract the phase lag caused by the control circuitry and the electromagnet, phase lead needs to be added. In control terms, the position of the levitating object is insufficient information to maintain stable levitation; the rate of change of position is required as well, i.e. the speed. This can be achieved with the basic circuit below.

Fig5: Diagram showing a simple phase lead circuit



This circuit would be positioned between the position sensing circuitry and the current control circuitry. As a heuristic, R2 is usually one tenth of R1 (to limit AC current). C2 is determined based on the cut-off frequency, i.e. the frequency of the oscillation that must be eliminated. This is determined according to the equation:

$$f = \frac{1}{2\pi RC}$$

f = frequency of oscillation (Hz)
R = R1 (ohms)
C = C1 (farads)

The position information is the dc signal and passes through the resistor R1, giving it the appropriate gain. To obtain the speed, the position information is differentiated with the resistor and capacitor combination in series. This is indicated by R2 and C1 in parallel with R1. Thus both the position and the speed information are summed to determine what the driving current should be. When the levitating object is still or moving slowly, the position information is dominant. If the object starts rising or falling quickly however, the speed information becomes more dominant in the calculation of the necessary current. Thus the effect of the acceleration of the object is nullified, and the unwanted oscillations in the levitation of the object are damped.

Fig6: Picture showing a magnetic suspension system in action.

Image from: http://www.oz.net/~coilgun/levitation/home.htm

6. ELECTROMAGNETIC LEVITATION

The main driving interest behind electromagnetic levitation is in its applications in mass transport. Much research is being done on the methods and complexities of this technology. In its applications in mass transport, particularly trains, this technology is loosely referred to as MagLev.

6.1 MAGLEV

This concept has already found commercial application in maglev trains. MagLev is an acronym for **mag**netic **lev**itation, and is most commonly used when referring to trains. MagLev is desirable in such an application because of the low maintenance for the track networks, and the low friction track that it provides. Because many trains gain their energy from sources not on the actual train, the energy requirements of the system become less stringent. Therefore, even though, it takes a considerable amount of energy to levitate the train, the energy can be feasibly obtained and transferred to the train.

6.1.1 Design Considerations

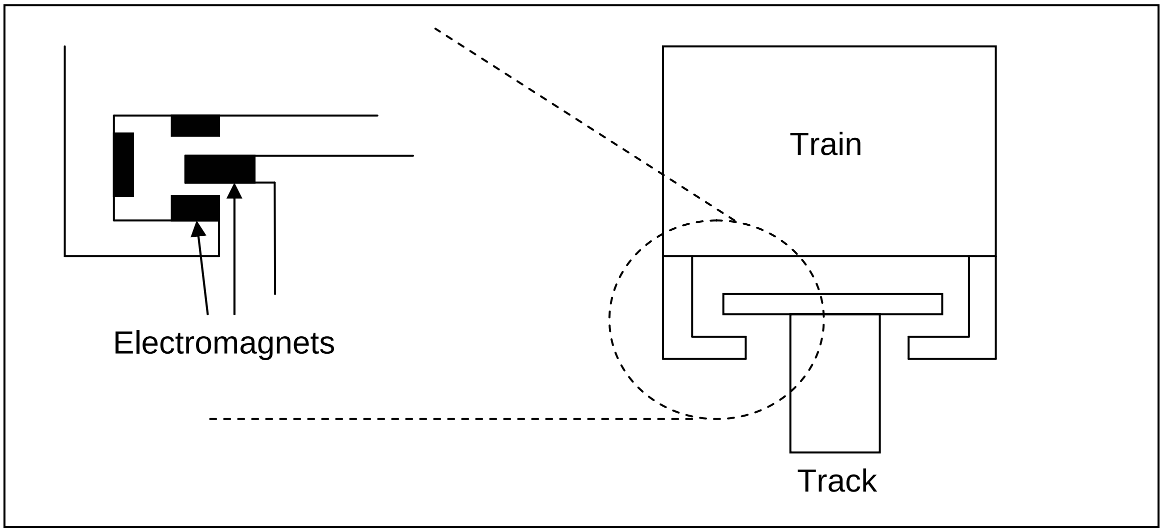
Various things need to be taken into account when considering the levitation subsystem of a greater MagLev system. The most obvious considerations are the requirements to levitate the train. These include the force required to lift the train, energy consumption, drive systems (the way in which electromagnets are arranged and triggered which causes the train to move forward) and forces acting on the train as it travels at high speed through turns.

Apart from this are the constructional and cost considerations of such a system. For something as large as a train, these are quite important. The comfort of the passengers is a priority in such an application. Oscillations and sudden movements or accelerations are undesirable and can cause great discomfort to passengers. As such, the control requirements are very rigorous. Basically, the train must be kept, levitated, on track and moving forward with the ability to stop as required. All this must preferably be achieved through non contact methods, such as through the use of magnetic fields.

6.1.2 Existing Solutions

Earnshaw’s theorem must be taken into account. However, as in the case of the simple magnetic suspension system, MagLev seeks to circumvent Earnshaw’s theorem through the use of feedback. There is however still some research being done on using permanent magnets for this application. The biggest strides however, are being made with electromagnets and feedback control. Using feedback and electromagnetic levitation, solves the fundamental problem described by Earnshaw. The next issue of concern is useful levitating stability. The various means of achieving this are through different arrangements of electromagnets. These take advantage of either magnetic suspension or magnetic levitation or both. Due to the rigid nature of the train’s structure, and the fact that it must travel down a guided path, the configurations of the electromagnets on the train and on the track become simpler. Below is a diagram of a simplified arrangement of electromagnets for MagLev systems.

Fig7: Diagram showing a simplified arrangement of electromagnets to levitate a train.



The sideways motion of the train is just as important as the up and down motion of the train. Thus the problem of magnetic levitation has shifted from being a one dimensional problem as in the case of magnetic suspension, to a three dimensional problem. Maglev train systems solve this by various arrangements of electromagnet such as those depicted above. The designer can then focus on the characteristics that are required of each electromagnet, and then their relation to each other.

The relation or interaction between the various electromagnets is also vital. Movement and shifts in momentum of the train can not only affect the control circuitry of one electromagnet, but the individual circuits can have negative effect on each other. The train can begin oscillating if there isn't some form of transfer of control information between the various control circuits of the electromagnets. The same form of over compensation in control systems as those discussed in the case of magnetic suspension can occur in the maglev system if there is not a means for the various control circuits to interact.

Newer developments in MagLev technology include research into levitation with superconductors and other diamagnetic effects. These include superconductor magnets housed in the train, repelling cheap, easy to construct magnets built into the track. Diamagnetic effects being exploited include oscillating methods as described earlier. Such a system uses magnets housed in the train to repel AC current carrying conductors housed in the track.

The advantage of using diamagnetic effects to perform magnetic levitation is that that compared to a system using electromagnets for levitation, a system using diamagnetic effects has a significantly larger air gap.

6.2 THE MAGLEV CRADLE

The aim of this thesis was to produce a working magnetic levitation system capable of levitating an object clear of any support, without magnetic field sources placed along side it on the same level of elevation. Only one such similar system was found to exist. It is called the “MagLev cradle” and was designed and built by Bill Beaty.

6.2.1 Operation

The MagLev cradle works by simulating the Meissner effect electronically. The circuit simulates it in that it repels both north and south poles. The basic premise of the system is that a hall sensor is placed on one end of an electromagnet. The sensor output is sent to the current control circuitry of the electromagnet after being properly modified with the correct gain and polarity. The circuit is set up so that it attempts to maintain a resultant magnetic field of zero within the hall sensor. This means that as a magnet with, for example, the south pole exposed to the sensor, approaches the sensor, the circuit will increase the current in the electromagnet in the necessary direction to produce an opposing south pole from the electromagnet. As the magnet moves closer to the sensor, the circuit will drive the electromagnet with more current until the force is great enough to match the weight of the magnet. This will also occur if the north pole of the magnet is exposed to the sensor, thus the circuit emulates the Meissner effect.

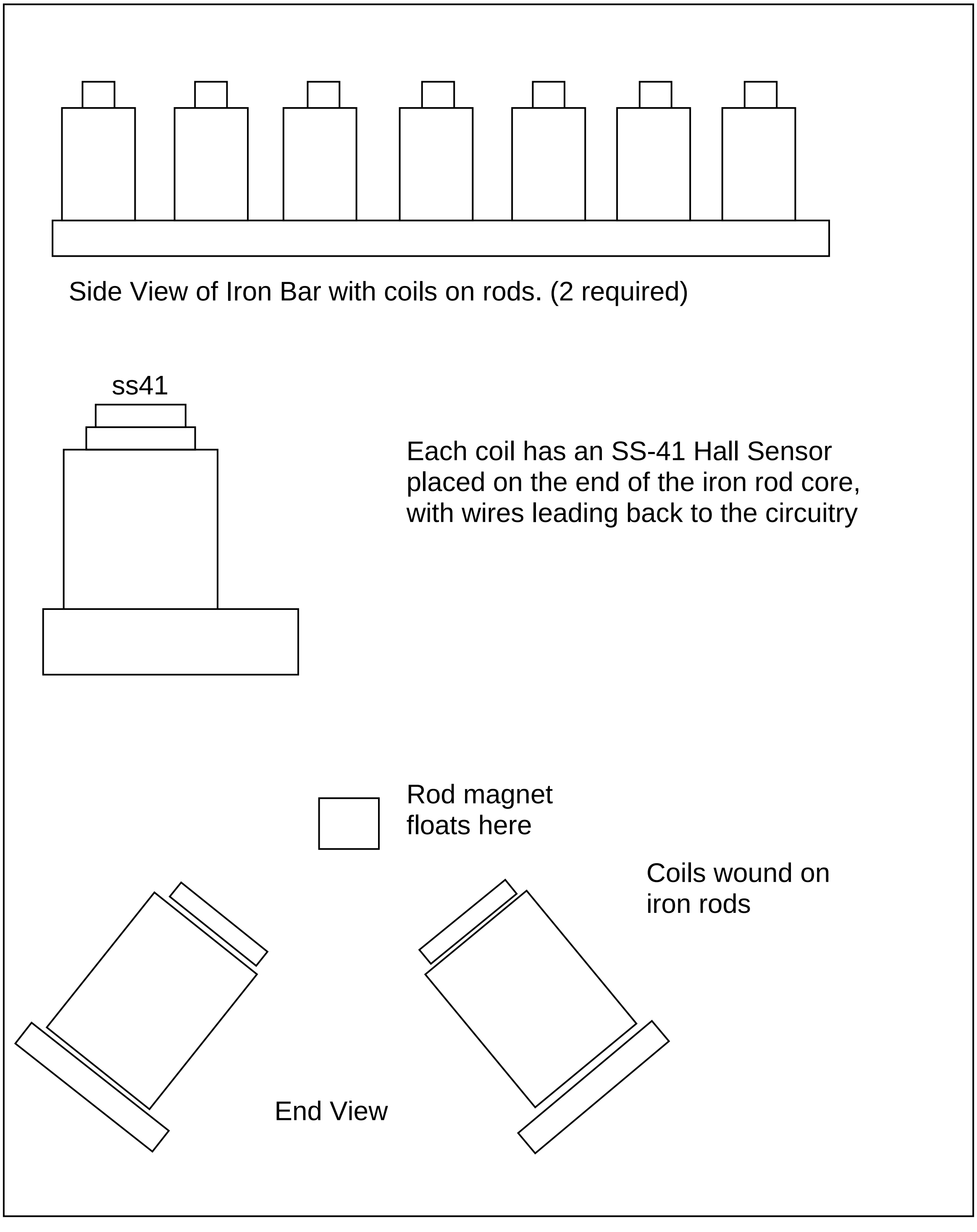
The MagLev cradle utilizes an arrangement of up to 12 such electromagnets and their control circuits in a “v” configuration to levitate a bar magnet. A “v” configuration is used to overcome any sideways motion the bar magnet may experience and thus keeping it trapped in position, levitated above the electromagnets. The MagLev cradle uses rapid switching circuits to control current to the electromagnets. The amount of time that the circuit remains on is a function of the distance of the bar magnet. If the bar magnet falls too close to the electromagnet, the circuit switches on, thus applying more repelling force. If the bar magnet rises too high above the electromagnet, it turns off, thus removing the repelling force. The bar magnet gradually reaches an equilibrium height, where the electromagnets are constantly switching on and off to maintain the levitation height. It may seem that this system would inherently cause the bar magnet to oscillate in the air. This oscillation is damped by the inertia of the bar magnet. The switching speed is so high, that the inertia of the bar magnet keeps it stationary in mid air.

6.2.2 System Problems

It was observed however that system suffers from instability. The bar magnet can only remain levitated for a few seconds before the oscillations become too great and it falls. This is most likely due to the phase lag problem identified in the magnetic suspension system. The solution is also most likely to add phase lead into the circuit, i.e. to obtain the speed and add it to the position information in order to damp this oscillation. As Beaty noted, this damping could also be achieved physically by placing copper plates perpendicular to the levitating bar magnet. If the bar magnet oscillates, an electric current will be induced in the copper plate, causing an opposing magnetic field to be established, which will damp out the bar magnet's movements. It was also noted that weights could be added to the bar magnet to increase its inertia and in effect damp out the oscillations in that way. This solution however would have undesirable effects on the system's performance. Things like the levitation height and the speed of response (due to the levitating object being heavier) would be adversely affected.

To repel both north and south poles, the magnetic cradle requires a split power supply in order to provide different current directions in the electromagnet as required. A simple transistor switching circuit controls the average amount of current the electromagnets receive based on sensor information. The position sensing is done with hall sensors mounted on the ends of the electromagnets. The physical layout of the MagLev cradle is shown below.

Fig8: Diagram showing the physical setup of the MagLev cradle.



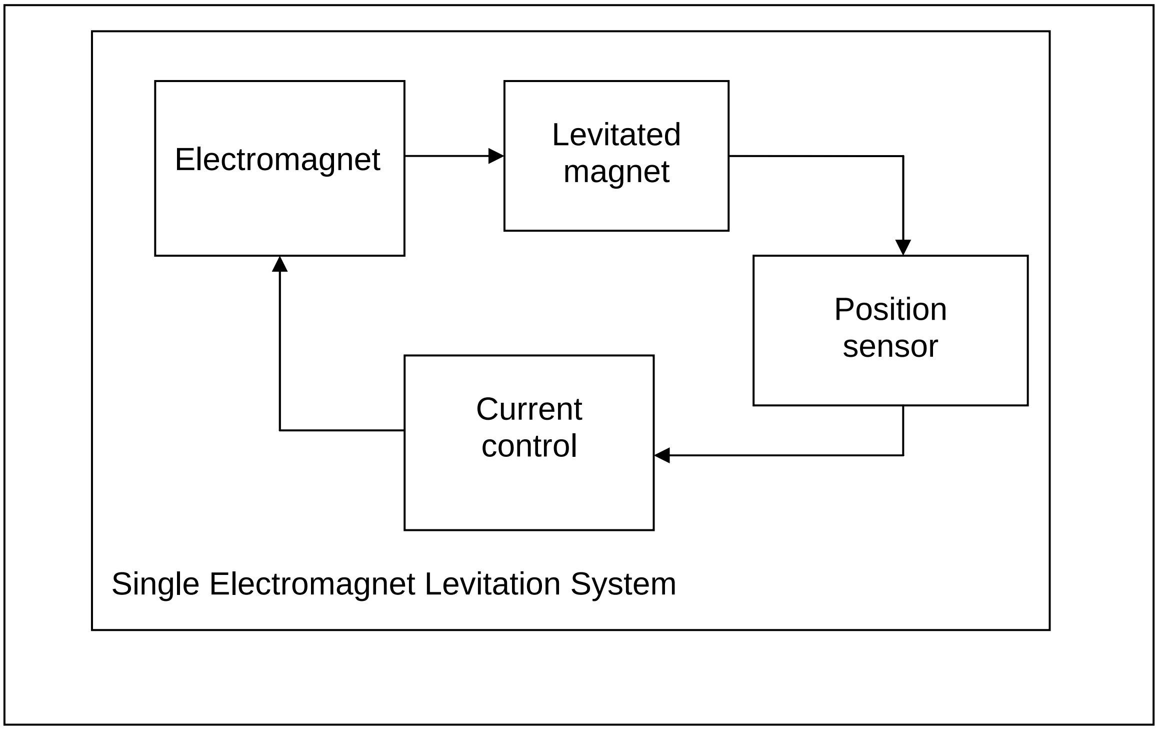
Each coil has an SS-41 Hall Sensor placed on the end of the iron rod core, with wires leading back to the circuitry

7. Electromagnetic Levitation System Development

The model developed for this thesis topic aimed to use continuous current control to the electromagnets, instead of the switched current control used by the MagLev cradle. Experiments were also done to investigate various configurations of electromagnets in order to achieve stable magnetic levitation. The current control circuitry and Hall Effect sensor system, would be tested first, and then duplicated for each electromagnet added to the system. From there, control circuitry would be designed and added as necessary.

7.1 SYSTEM OVERVIEW

Fig9: A diagram showing a systems view of a magnetic levitation device.

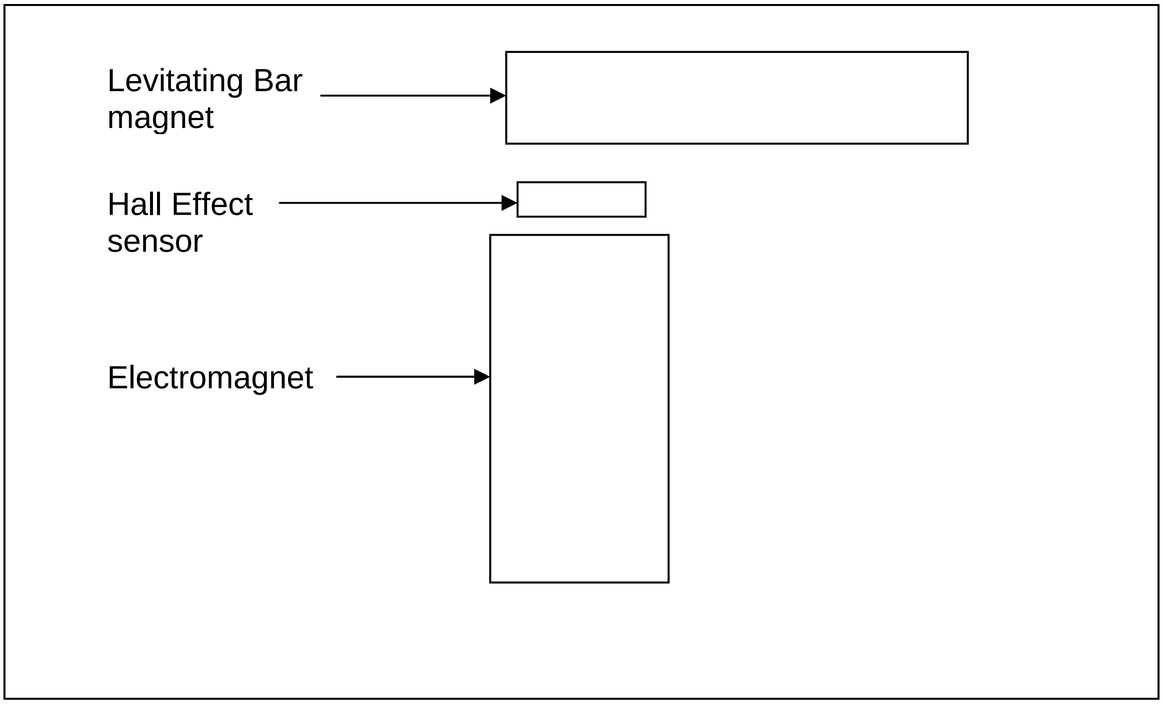


As is the premise with most magnetic levitation models, the system diagram above shows the basic working of a magnetic levitation system. Because the system designed for this thesis is simply made up of multiple electromagnets, the above system diagram applies to each one. The interaction of these systems will be discussed later on.

As in the MagLev Cradle, the operation of this system will be to detect the position of the levitating magnet and drive the electromagnet accordingly. If the magnet falls too close, the current in the electromagnet must be increased to repel the levitating magnet more strongly. If it rises too high, the current in the electromagnet must be reduced.

For this model, the object being levitated will be a bar magnet. The means of sensing the position will be done by sensing the magnetic field of the levitating magnet. The physical arrangement of the above system will be as follows.

Fig10: Shows a possible physical arrangement for a magnetic levitation system.

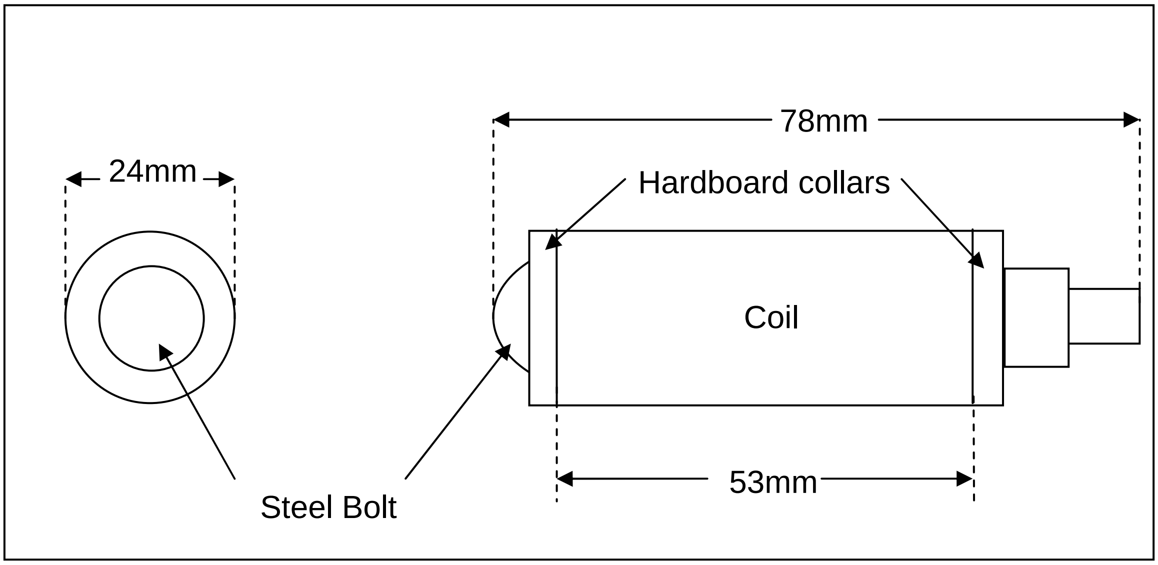


7.2 SYSTEM COMPONENT OVERVIEWS

7.2.1 Electromagnets

The electromagnets are steel bolts with thin copper wire wound around them. Two circular pieces of wooden hardboard are bolted to each end. The coil itself is wrapped in masking tape .The coil has a dc resistance of 22 ohms.

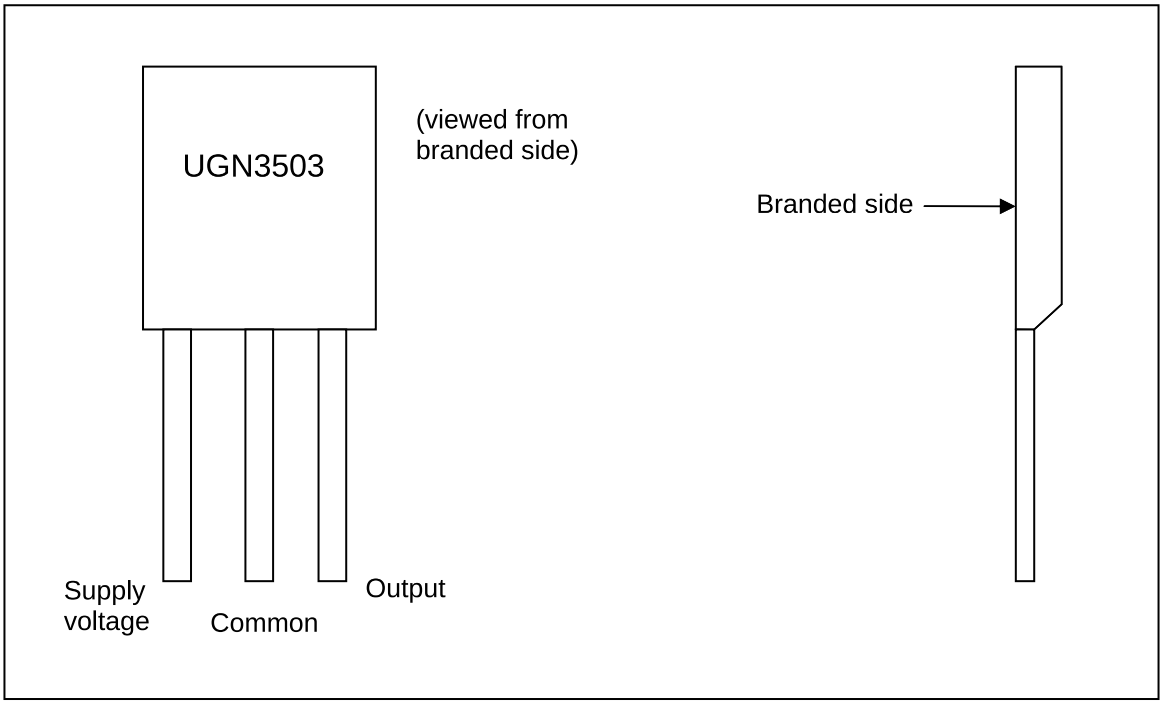
Fig11: Shows the physical dimensions of the electromagnets used.



7.2.2 Ratiometric Linear Hall Effect Sensors

The Hall Effect Sensors are linear output devices which sense the strength and polarity of nearby magnetic fields. Their part no. is UGN3503u. The sensor itself comes in a small three pin IC package. Its supply voltage is 4.5V - 6V and the supply current required is approximately 9mA – 14mA. It outputs a quiescent voltage of 2.4V – 3V depending on the supply voltage. The sensor sensitivity is dependent on the supply voltage, but it is generally in the range of 1.4mV/G.

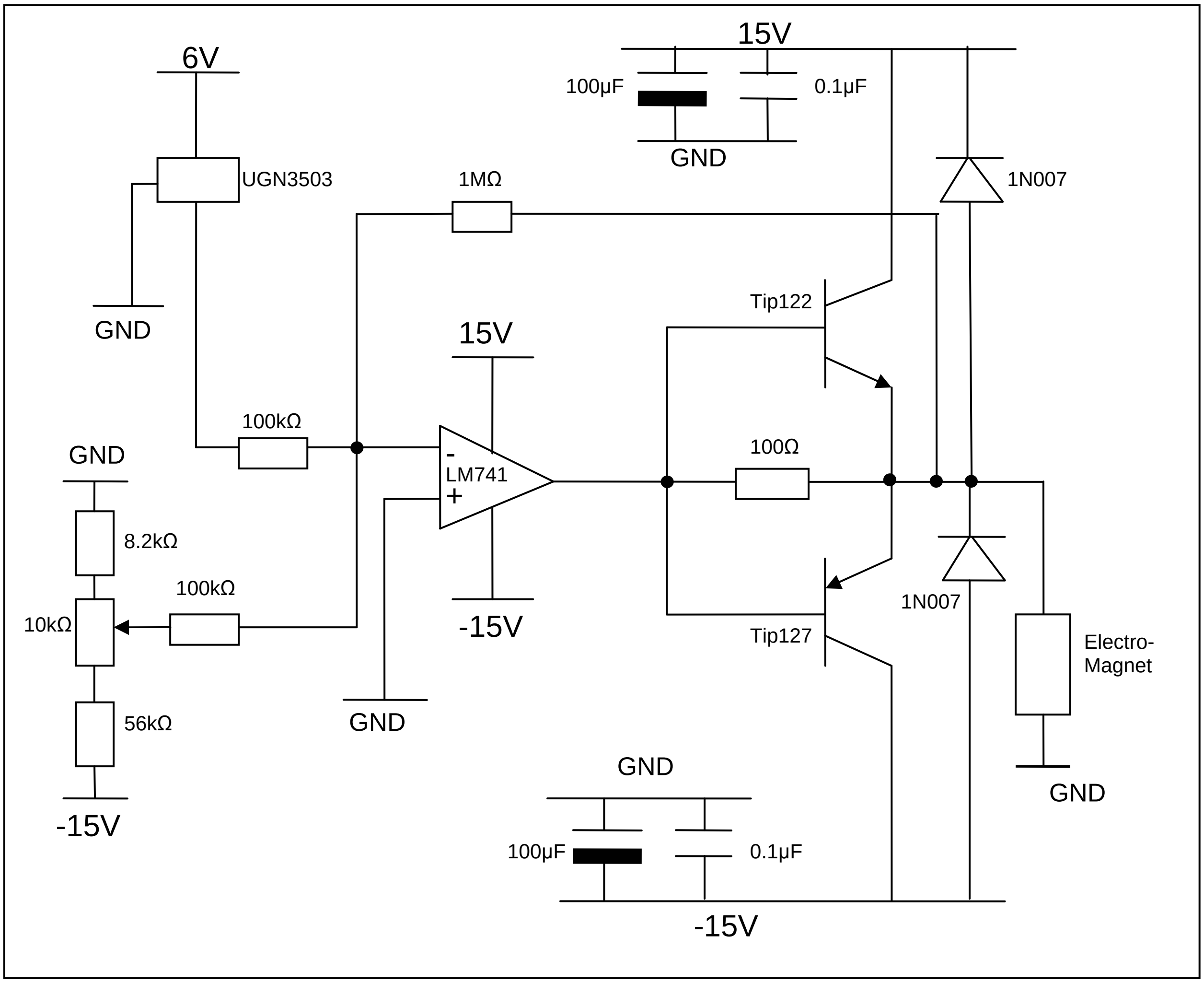
Fig12: Pictorial representation a Ratiometric Hall Effect Sensor.



7.3 ELECTROMAGNET CURRENT DRIVE CIRCUIT

The first current control circuit attempted is shown below.

Fig13: Circuit diagram of a one opamp current control circuit.



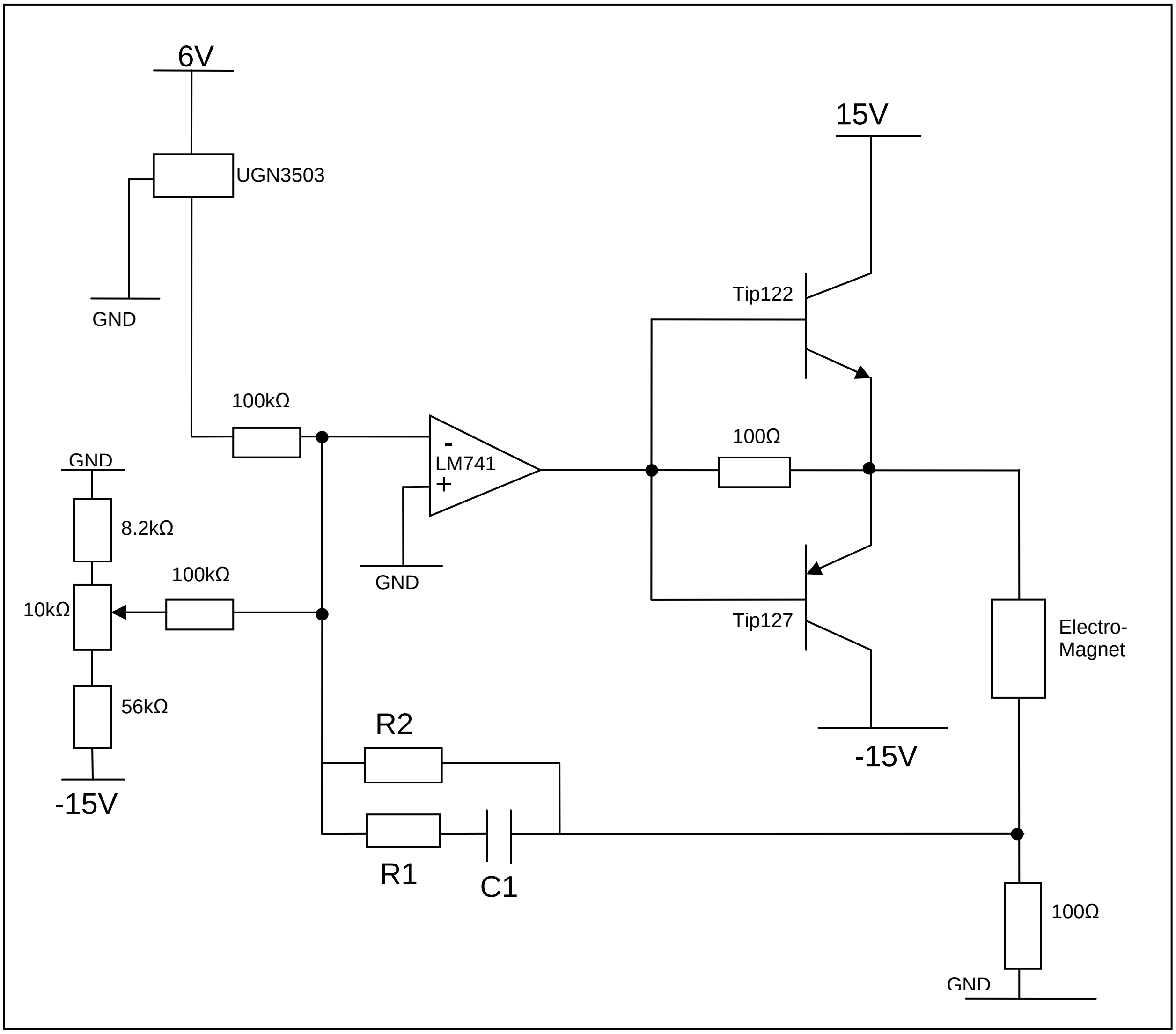
The Hall Effect sensor (part no. ugn3503u) has a quiescent output voltage of 2.4 volts to 3 volts. This is dependant on the sensor's supply voltage. The sensor indicates whether a north pole or south pole is detected, by raising or lowering its output voltage about its quiescent value. As the approaching magnetic field strength increases, the output voltage will increase or decrease linearly, depending on which magnetic pole it is exposed to. For the current in the electromagnet to be able to reverse direction based on this information, the sensor output would have to be made bipolar.

The opamp is used in its virtual earth configuration as an opamp summing circuit. The potentiometer in the resistor divider is used to null out the quiescent voltage of the sensor, by summing an equal and opposite voltage in to the virtual earth point. Thus, at the opamp output, a bipolar signal is achieved, with its polarity indicating which magnetic pole has been detected, and its magnitude indicating the strength of the detected magnetic field. The feedback resistor provides the gain required to increase the small dc response from the sensor to a usable level. The two Darlington power transistors are connected in a sink/source configuration with the load, and their bases are driven by the opamp output. This setup emulates a power opamp, by allowing a basic LM741 opamp to control a current much larger than its specified rating.

The 100 ohm resistor between the transistor base and emitter allows a small current to flow to magnetize the electromagnet even when a very weak field is detected. The diodes were added to provide current surge protection, (even though the Darlington transistors already have built in diodes), and the capacitors to eliminate power supply noise.

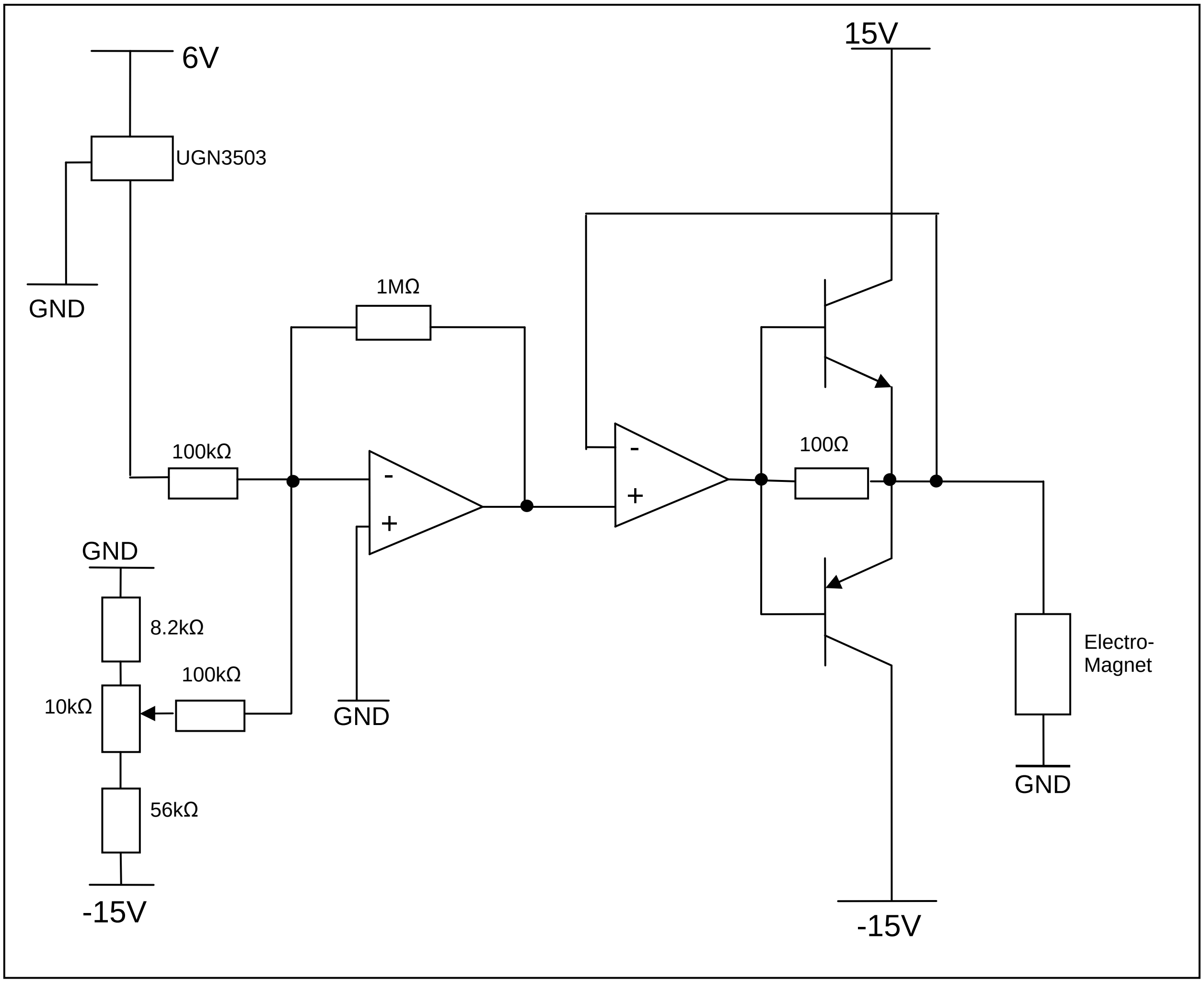
The system was promising in initial testing without the load. When the electromagnet was added however, the circuit suffered from severe instability. As soon as the voltage across the electromagnet reached approximately 1.2 volts (i.e. as soon as the transistors turned on) the instability appeared as the output voltage oscillated. Initially, successively larger capacitances were added across the feedback resistor. Even though this did reduce the magnitude of the oscillations across the load, they could not be eliminated. Also the introduction of such large capacitances was hampering the speed of response of the system. Next, a resistance was placed in series with the electromagnet. This did reduce the magnitude of the oscillations, however, as the value of resistance was increased, the amount of current in the electromagnet had bee so drastically reduced that this solution was no longer feasible. Because the problem only occurred when the electromagnet was added, it was assumed that the oscillations were caused by the phase lag introduced by the electromagnet. Thus the circuit was modified to the one below in order to facilitate the introduction of phase lead.

Fig14: Circuit diagram of a current control circuit with the addition of phase lead.



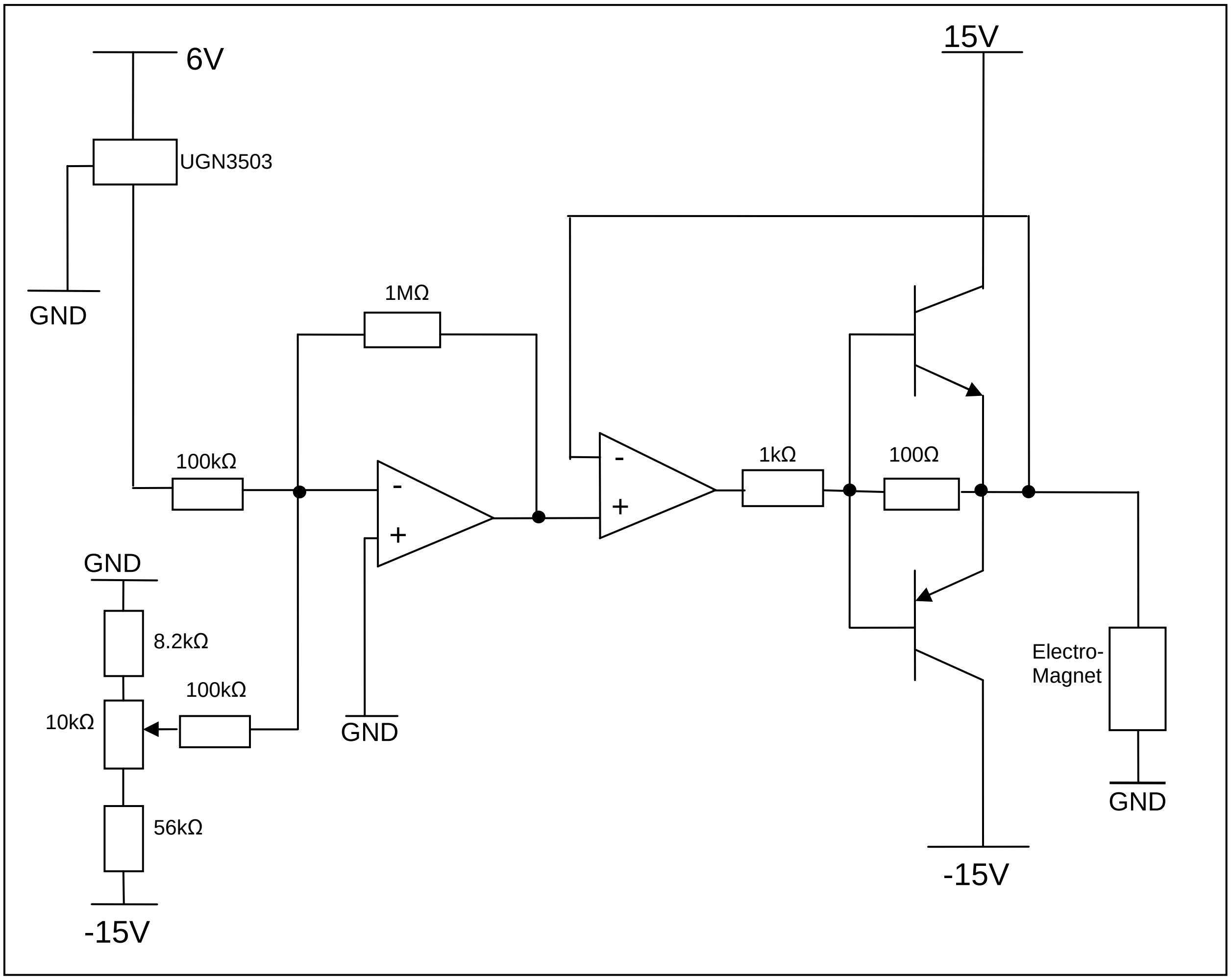
This circuit performed current feedback by measuring the current through the 100 ohm resistor connected in series with the electromagnet. The phase lead was then added into the feedback path in an attempt to correct the phase lag of the electromagnet. The initial phase lead modification, and the variations that followed, failed to have any effect on the oscillation frequency, or amplitude. Unable to eliminate the oscillation at this stage, a voltage feedback solution was experimented with. The circuit below had only a slight improvement over the original.

Fig15: Circuit diagram of a current control circuit using two opamps.



This circuit separated the opamp summer circuit and the current drive circuit. The amplitude of the oscillations was reduced; however, it was observed that a very high frequency of oscillation still existed, in the order of 7 MHz. This oscillation appeared when the voltage across the load rose to over 2.38 volts. This indicates that the oscillations appear very shortly after the transistor turns on. Various changes were made to the physical layout of the circuit in an attempt to eliminate the oscillations, suspecting that they were caused by poor circuit configuration. These changes proved ineffective in minimizing the amplitude of the oscillations or altering its frequency. This lead to the modification shown below:

Fig16: Circuit diagram of a two opamp current control circuit with the addition of a transistor stage gain limiting resistor.

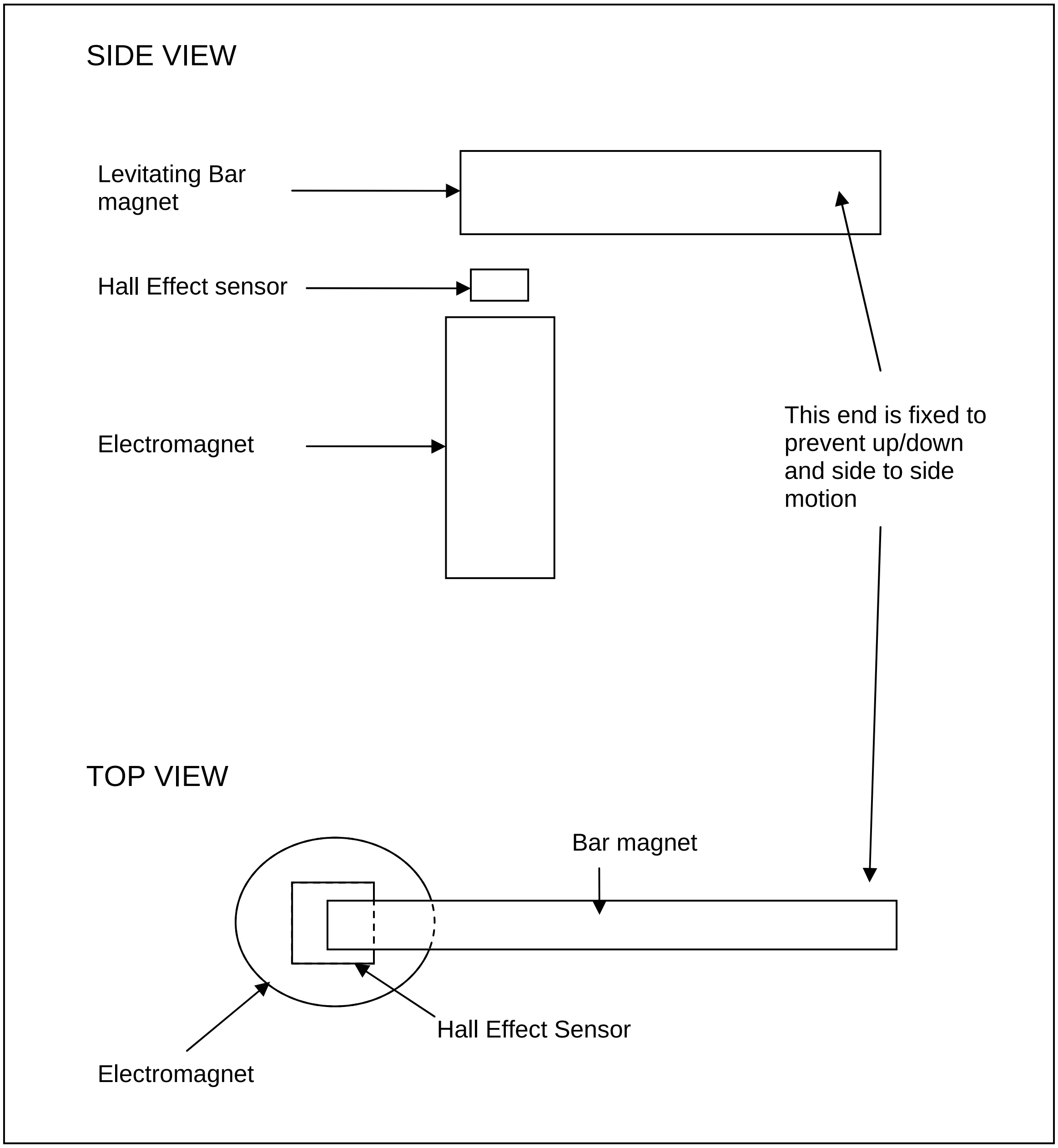


The resistance added between the opamp output and the transistor bases effectively reduces the gain of the transistor stage by creating a voltage divider with 100 ohm resistor and the load. This modification was found to completely eliminate the oscillations and instability at the cost of maximum voltage that could be attained across the load. It would also suggest that using TIP31 and TIP33 transistors instead of TIP122 and TIP127 transistors would also have solved the oscillation problem (due to the former transistor pair having a lower current gain). This resistance was gradually reduced until a trade off was established. It was found that a resistance of 82 ohms eliminated the oscillations while providing the largest possible voltage across the load, which was approximately 10 volts. This modification proved to stabilise the original circuit used in the first attempt as well. Thus both the latest design and the original one could be tested for performance.

7.4 INITIAL ELECTROMAGNETIC REPULSION TEST

The next step was to test the magnetic repulsion of the system. To test this, the following arrangement was established.

Fig17: Diagram showing the physical layout of the magnetic repulsion tests.

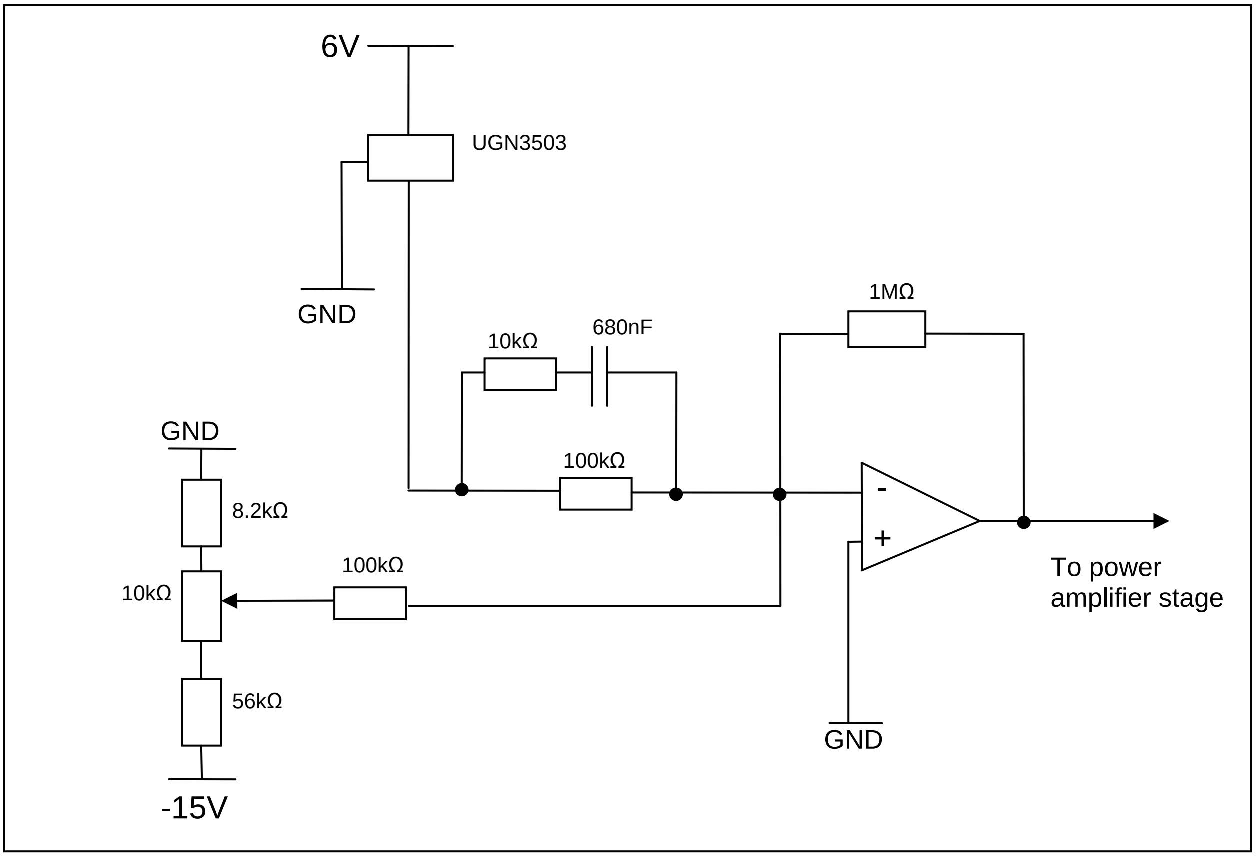


Keeping one end of the test magnet steady, the other end was brought into proximity of the Hall Effect sensor which was attached to the electromagnet. The Hall Effect sensor was placed on the centre axis of the electromagnet. It was noted that the circuit is sensitive to the orientation of the electromagnet, i.e. which way round it is connected. If the electromagnet is connected the wrong way, then an approaching south pole for example, will cause the circuit to produce a north pole from the electromagnet. This would be contrary to the intended operation of the circuit and it would enter an unwanted mode. Thus it is important to connect the electromagnet the right way around.

“You want negative feedback and proportional control rather than positive feedback and latchup.” Beaty, B. “Maglev Magnetic Levitation Suspension Device”. [online] http://amasci.com/maglev/magschem.html [October 2005]

Having done this correctly it was further observed that when the magnet was brought close to the sensor it began to “bounce”. This was effectively an oscillation of approximately 0.5 Hz which grew in amplitude until the bar magnet was thrown clear. This is basically a manifestation of the problem identified in the magnetic suspension system. Due to the phase lag of the electromagnet and the circuitry, the position information is simply insufficient to stably levitate an object. Therefore, phase lead needed to be added to the system. This phase lead modification was as follows.

Fig18: Circuit diagram of the two opamp current control circuit with the addition of phase lead. The right side of the complete circuit has been removed for simplicity.

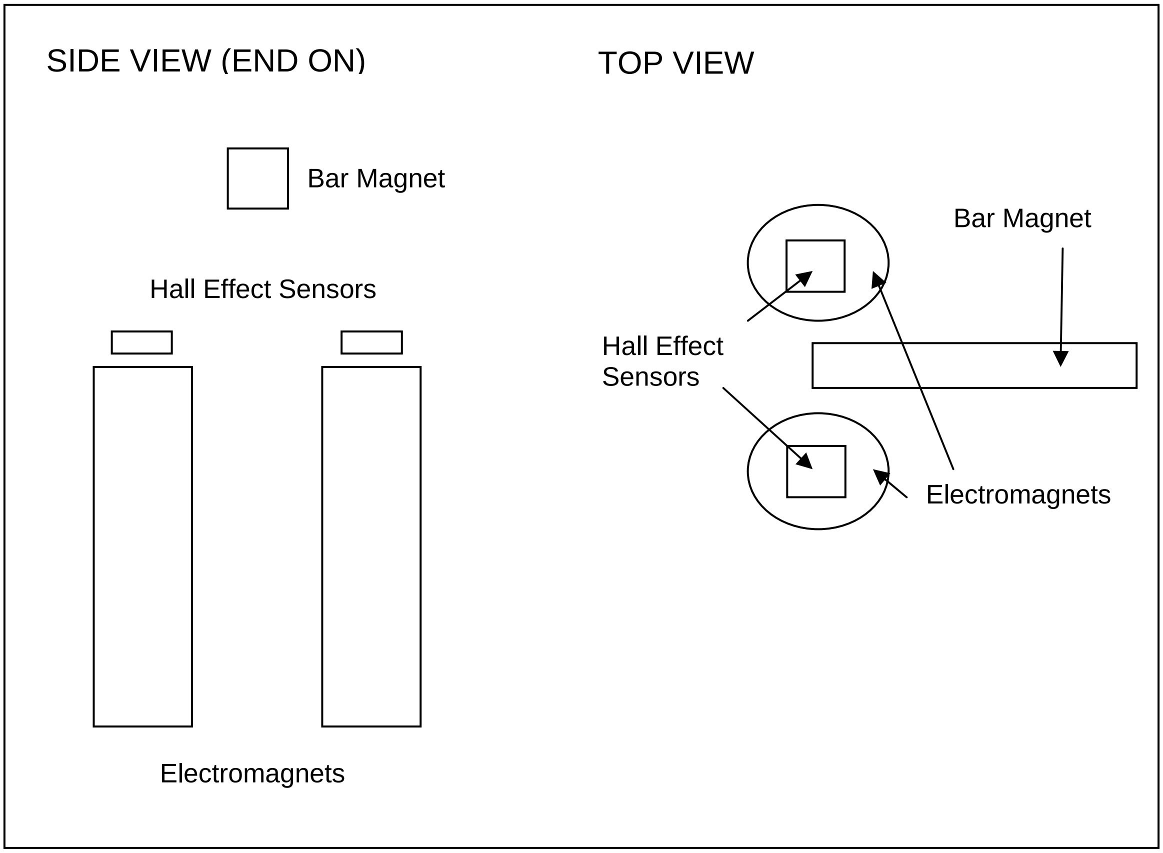


The capacitor chosen was simply the largest manageable ceramic capacitor available. Due to the low frequency of oscillation, 680nF proved sufficient to completely eliminate oscillations in the movement of the bar magnet. From these experiments it was observed that the area of maximum magnetic repulsion was very small, and was found in the area directly above the Hall Effect sensor. Out side of this region, the force of magnetic repulsion decreases quite rapidly. Field strength falls to almost half with a deviation of as little 0.5 cm from the ideal region.

7.5 PARTIAL ELECTROMAGNETIC LEVITATION TEST

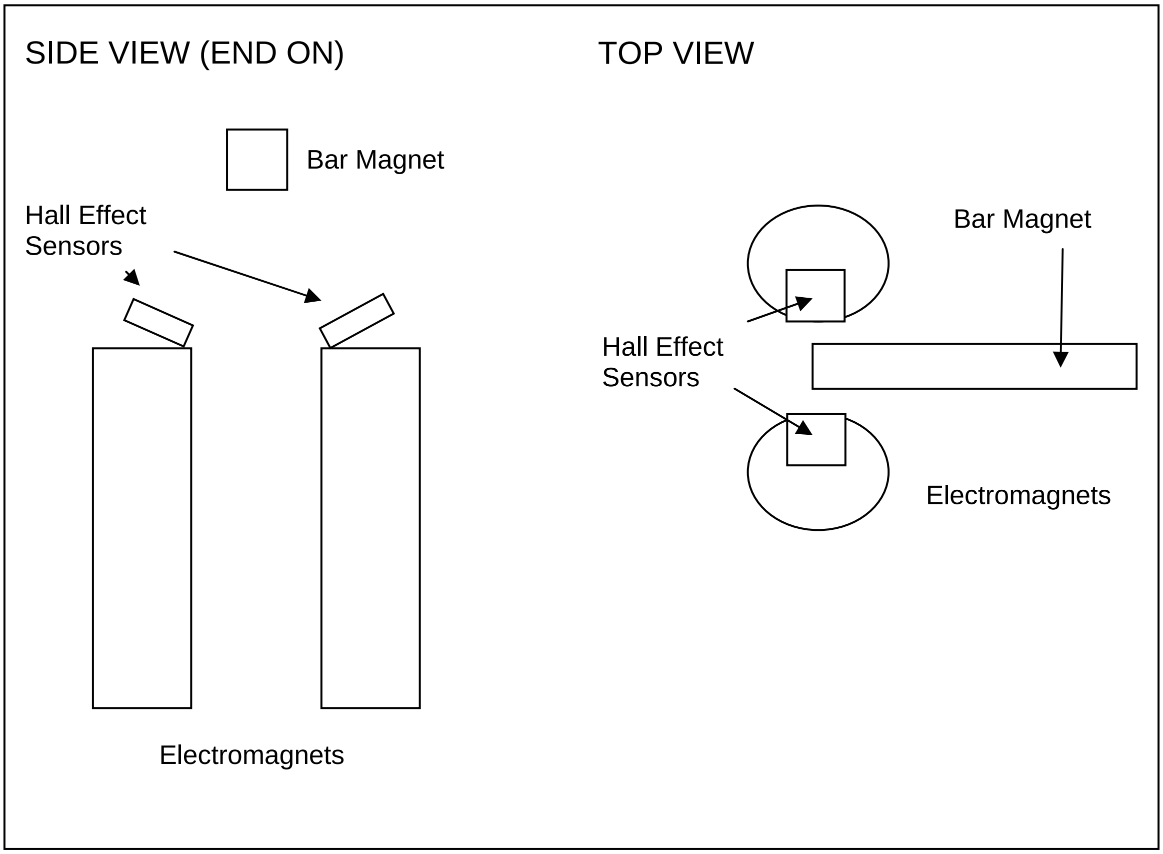
The next experiment involved testing how well an arrangement of two electromagnets could successfully levitate one end of a bar magnet if it is only supported in two directions. The configuration of two electromagnets along side each other depicted below was used.

Fig19: Diagram showing the physical layout of the partial magnetic levitation tests.



As explained above however, because the area of maximum magnetic repulsion is so small, there was insufficient magnetic field strength at the desired point of levitation. This resulted in the bar magnet dropping in between the two electromagnets, which were unable to repel it. To counter this, the area of maximum effect was moved by changing the orientation of the Hall Effect sensors. Instead of placing them on the centre axis of the electromagnet, they were placed off the centre axis in such a way that they were facing the levitating magnet.

Fig20: Diagram showing sensor positioning modifications.



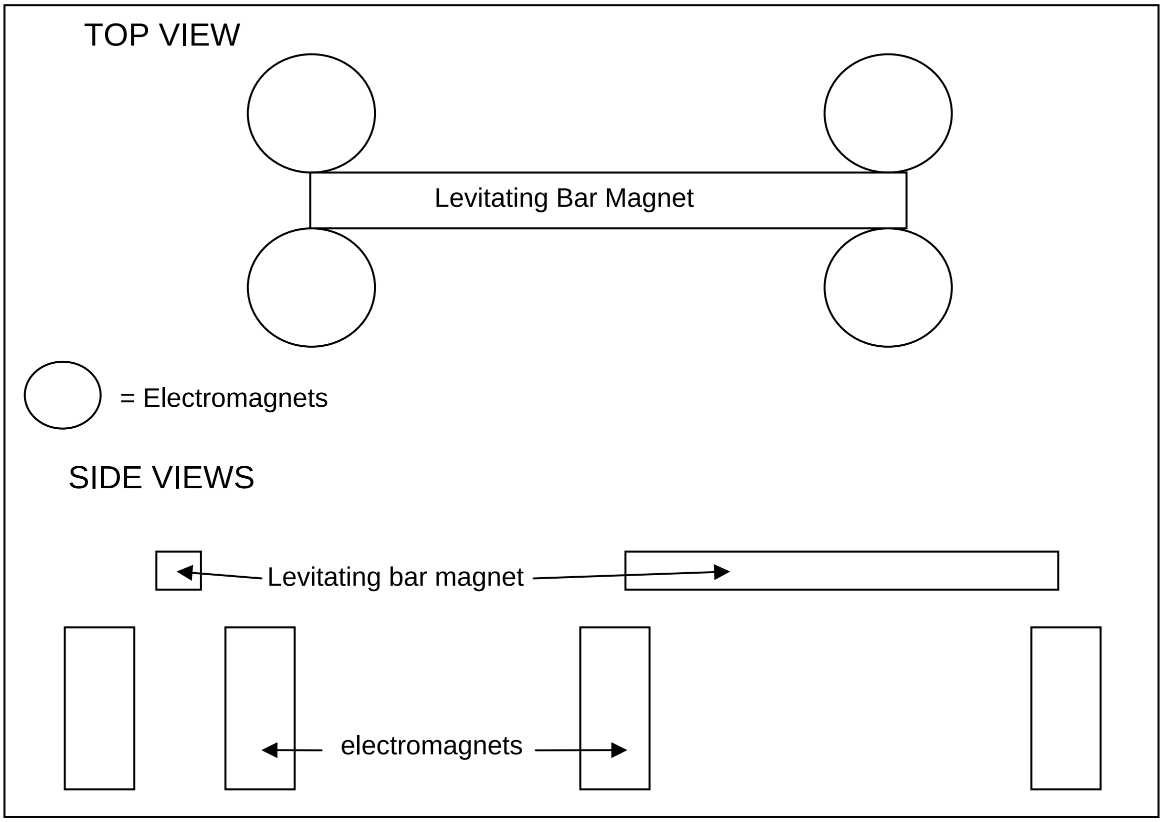
This arrangement was successful in levitating one end of the bar magnet which was only supported in two directions. The added advantage of placing the hall effect sensor off the centre axis of the electromagnet, instead of changing the angle of the electromagnet, is that it makes the circuit send more current to the electromagnet, than is needed to repel the bar magnet. By placing the Hall sensor in this way, the back face (the side attached to the electromagnet) sees a weaker part of the magnetic field the electromagnet is producing. Thus to match the strong approaching magnetic field of the bar magnet, the circuit adjusts the electromagnet’s current to an amount that will make the weaker part of its magnetic field equal to the strong magnetic field of the bar magnet.

7.6 FULL ELECTROMAGNETIC LEVITATION TESTS

7.6.1 Magnetic Levitation Tests (4 Electromagnets)

Extending the success of the previous stage, where two electromagnets could effectively levitate one end, the next step was to attempt total levitation with four electromagnets. The arrangement shown below was used.

Fig21: Diagram showing the physical layout of the 4 electromagnet full levitation test.

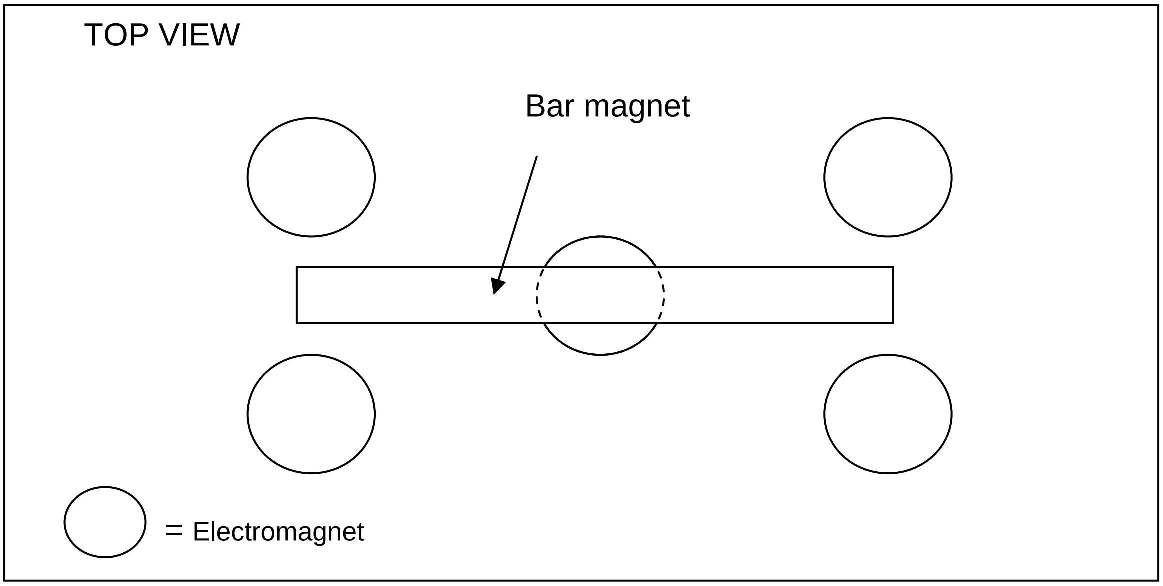


The above system was very sensitive to the positioning of the electromagnets. If the electromagnet pairs were too far from each other, the bar magnet would easily fall in between. If they were too close, then a slightly weaker part of the magnetic field of the bar magnet would be exposed to the Hall Effect Sensors. The result is that the electromagnets do not get enough current, and the bar magnet will drop. The system is less sensitive to the distance between electromagnets in a group repelling the same magnetic pole. If the Hall Effect Sensors were properly positioned on the surface of the electromagnet, then levitation of one of the magnetic poles of the bar magnet could still be achieved.

7.6.2 Magnetic Levitation Tests (5 Electromagnets)

To try to solve the problem identified in the first experiment, the following configuration was attempted.

Fig22: Diagram showing the physical layout of the 5 electromagnet magnetic levitation tests.



The reason for attempting this particular solution was to observe if the sideways motion could be stopped with the addition of only one electromagnet. The premise of this system is that, if the bar magnet is stationary in the correct position, i.e. with the centre of the magnet positioned directly above the centre electromagnet, then that electromagnet would not draw any current. This is because the magnetic field of a bar magnet is at its weakest at the centre. Thus the Hall Effect sensor wouldn't detect a significant field and the centre electromagnet would be off.

If however the bar magnet begins to slide, then there would be a stronger magnetic field above the centre electromagnet. This would cause the current control circuit to magnetize the centre electromagnet and repel the stronger magnetic field of the approaching end of the bar magnet.

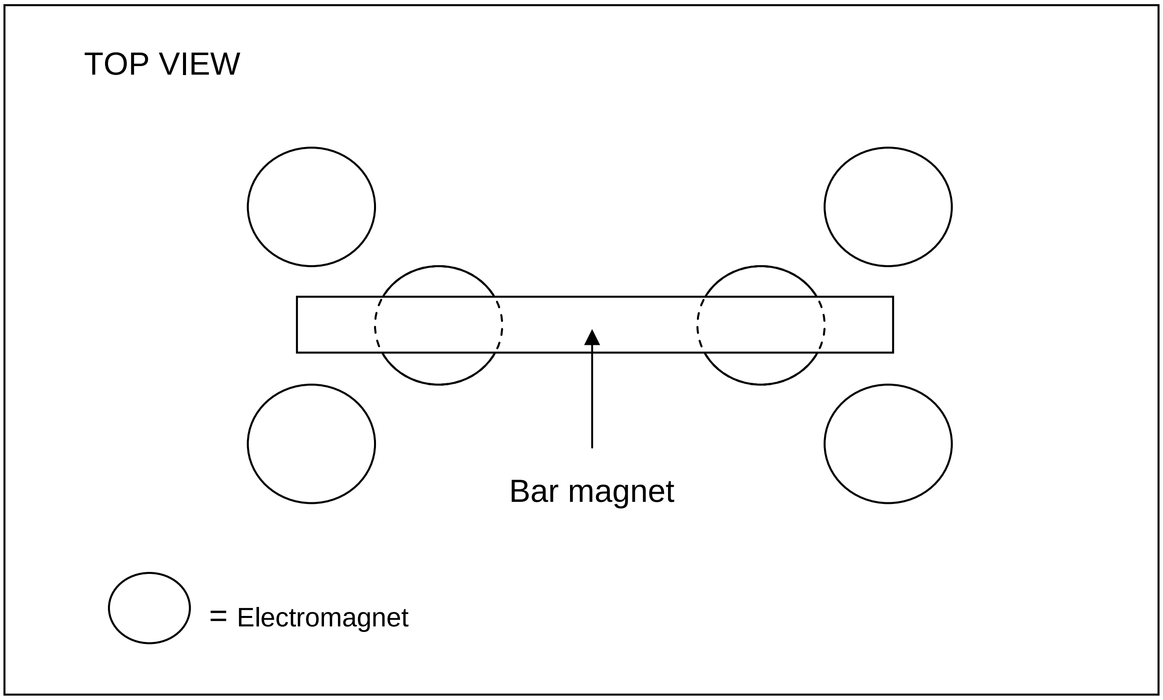
This solution didn't work in actuality, because the strength of the magnetic flux at the centre of the bar magnet was not strong enough. Thus, the centre electromagnet could not create a large enough repelling forces quickly enough to stop the sliding motion of the electromagnet.

7.6.3 Magnetic Levitation Tests (6 Electromagnets)

7.6.3.1 First Configuration

Of this number of electromagnets, two arrangements were tested. The first was the following.

Fig23: Physical layout of the 6 electromagnet magnetic levitation tests. (1st configuration)



In the above configuration, the extra electromagnets are placed in between the outer pairs. It was found that even though the bar magnet was directly above an electromagnet setup to repel it, it was at the ends of the bar magnet that the most significant repelling force occurs. Thus the middle electromagnets prevent the ends of the bar magnet from sliding past them. At the same time the middle electromagnets can assist with providing levitating thrust.

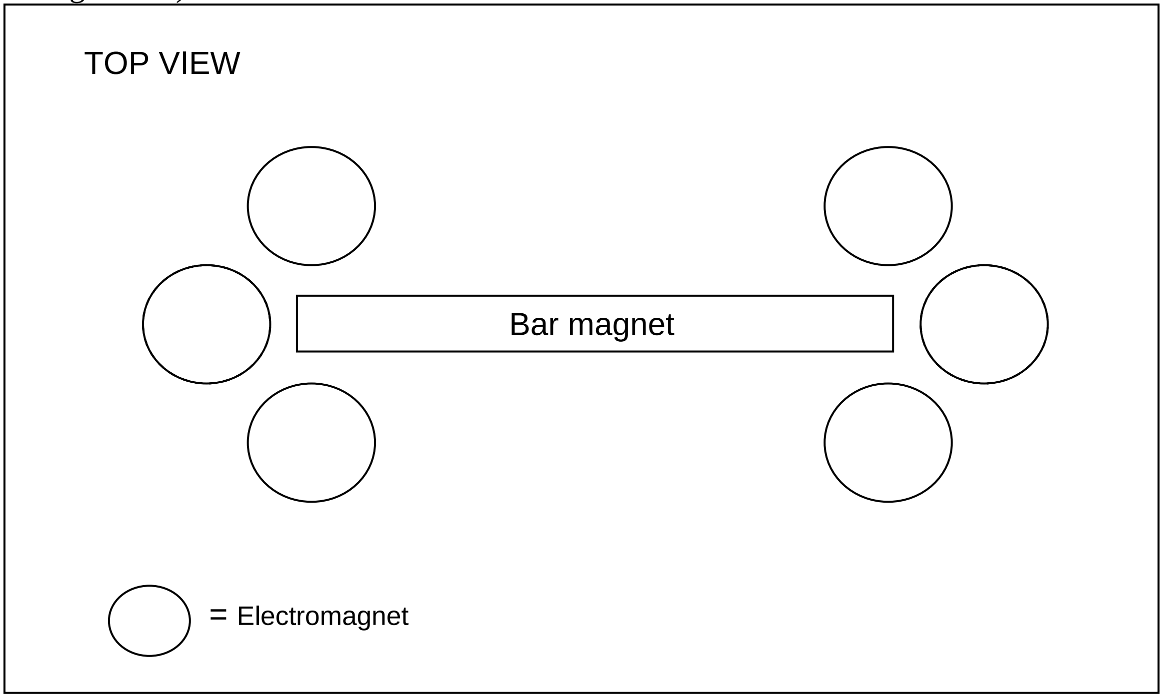
7.6.3.2 Observations (1st configuration)

Despite the now larger levitating area created by the three electromagnets, the bar magnet still tended to slide off the ends. Because the inner electromagnets were directly beneath the levitating magnet, the bar magnet tends to slide off the end and off to the side. This lateral movement of the bar magnet is as a result of the repelling force exerted by the inner electromagnets. This configuration, just like the previous ones, was very sensitive to the distance between the electromagnets. Even though marginal improvements were attained by adjusting electromagnet and Hall Effect sensor positions, the main problem of sideways motion of the bar magnet could not be stopped.

7.6.3.3 Second Configuration

The second configuration attempted was the design shown below.

Fig24: Physical layout of the 6 electromagnet magnetic levitation tests. (2nd configuration)



The problem in the previous configuration was that the bar magnet slid sideways and swivelled as it fell. This was because of the magnetic repelling of the electromagnets directly below it. To solve this problem, the inside electromagnets were shifted to the outside. In this configuration, all the magnetic repulsion force is concentrated below and to the outsides of the levitating bar magnet.

7.6.3.4 Observations (2nd configuration)

As with the previous configurations, care must be taken to properly align and space the electromagnets. The system used in this second test worked only marginally better than the first. It was found that as the bar magnet slid past one end it would in fact fall between the electromagnets as it fell.

8. Findings

At the time of completion of this report, stable magnetic levitation could not be fully achieved. As outlined above, the current system can only perform levitation of a bar magnet that is being supported in a lateral direction. The final problem proved to be a rather complex control one.

However, various observations could be made of the system to its current level of completion. Levitation using the electronically simulated Meissner effect is quite effective. Also, using the continuous current control method of driving the electromagnet makes integrating control circuit solutions relatively simple.

8.1 ELECTROMAGNET CURRENT CONTROL CIRCUITS

At the power amplification stage, it was found that having the inductive load of the electromagnet caused severe problems with the sink/source transistor configuration. Due to the current gain across the TIP122 and TIP127, when the electromagnet is added to the circuit, the output would oscillate at high frequencies. The instability causes great problems in the final system, because it means that the unstable electromagnet doesn't have equivalent magnetic repelling force to the other electromagnets in the system. This inherently makes levitation impossible.

This oscillation causes further problems if it crosses the zero volt thresholds. With the voltage across the electromagnet constantly changing, the magnetising of the electromagnet's steel core becomes affected. This causes the electromagnet's core to either magnetize too slowly or too quickly. This further complicates an already sensitive system.

If the output is oscillating it is also drawing current. This negates one of the desirable features of this circuit. Because the system tries to create a zero magnetic field within the Hall Effect sensor, if there is no foreign magnetic field, the electromagnet will not be fed current. In other words, even though the circuit is on, it will not draw significant amounts of current if there is no magnet to levitate. The electromagnet is only magnetized when a magnet to levitate is brought into proximity of the Hall Effect sensor. In the event of instability however, there exists an offset on the output, effectively causing the electromagnet to draw more or less current than it should.

Thus to eliminate this instability problem, a resistor can be added between the opamp (in the power amplification stage) and the transistor bases. As indicated earlier, this comes at a cost. A trade-off exists between the resistance required to eliminate the oscillation and the maximum voltage that can be acquired across the electromagnet. The highest voltage that can be attained across the electromagnet is determined by the saturation voltage of the opamp, and the resistor divider formed by the stabilizing resistor, the resistor for eliminating cross over distortion, and the electromagnet. Thus to increase the voltage across the electromagnet, one or all of these factors can be modified. To increase the saturation voltage of the opamp for instance, a variant of the 741 opamp can be used, which can accept supply voltages of ± 22V.

In monitoring the performance of the two versions of current control circuitry used, no significant difference was found. Thus a decision on which one to use in a future project would be based on the physical merits of each. Given this consideration, the preferable choice would be the original design. The necessary performance is achieved with just one opamp. This makes it a lot easier and quicker to construct. Because much of the experimentation involved testing various configurations and numbers of electromagnets, the circuit which can be built and debugged the fastest is more desirable. With fewer components in the circuit, there is also less that can go wrong.

8.2 TEST BED STRUCTURE

When testing the magnetic levitation capabilities of the system, it was found that the repulsion force between the levitating bar magnet and the electromagnet can be become so strong that the electromagnets themselves may begin to move, which would ruin any experiments done. In experimenting with various configurations though, one must still have the ability to quickly and easily modify and change the position of the electromagnets in relation to each other. In other words the arrangement must be flexible, but when an experiment is initiated, the configuration and electromagnets themselves must be firmly secure.

8.3 PHYSICAL ARRANGEMENTS OF ELECTROMAGNETS

It was found that the positioning of the Hall effect sensors on the surface of the electromagnet could change the position of maximum magnetic repelling force. To trap the bar magnet and prevent side to side motion, the maglev cradle used electromagnets positioned at an angle in a “V” configuration. By shifting the position of the Hall effect sensors, the same effect can be simulated, even though the electromagnets are mounted in an upright, vertical position.

The first configuration of electromagnets used to attempt to levitate the bar magnet was four, arranged in a rectangular shape. This configuration proved inadequate to achieve levitation. As outlined earlier, the problem was keeping the levitating bar magnet in the area above the electromagnets. Even though side to side motion was prevented by the electromagnets, the bar magnet still had a tendency to “slide” off the ends. The area of effective levitation proved to be very small, and the bar magnet would easily escape it if there was any discrepancy of field strength between the ends. Despite moving the electromagnets closer and further apart, the bar magnet could not be effectively trapped above the electromagnets.

To try to combat this sliding motion, another electromagnet was added to the system. This fifth electromagnet was added in the centre of the existing rectangular shape. Even though this centre electromagnet circuit had an increased gain in order to react to weaker magnetic fields, it was found that the magnetic field near the centre of the bar magnet was far too weak to be effectively repelled. Thus it could not stop the side ways sliding motion.

The next configurations attempted were various arrangements with six electromagnets. These arrangements attempted to trap the bar magnet’s magnetic field in a particular area, and in so doing keep the magnet in the area above the electromagnets. These still proved insufficient to stop the sliding motion of the levitating magnet. In doing these tests it was also found that if the electromagnets weren’t aligned directly under the area of strongest magnetic flux from the bar magnet, the levitating object would begin to oscillate from side to side. This would indicate that cross coupling of sensor information between the current control circuits is required.

8.4 CONTROL ASPECTS

In the initial testing of the repelling force of the electromagnets, it was found that oscillations were a large problem. The magnet would effectively “bounce” continuously until it fell clear. It was found however, that the addition of phase lead helped greatly in eliminating this problem. Even though the “bouncing” oscillations were of a very low frequency (approximately 2 Hz) it was advantageous to restrict the size of the capacitor in the phase lead circuit. This kept the speed of response of the circuit relatively quick.

As mentioned above, there was a problem with side ways oscillations in the bar magnet when the electromagnets weren’t properly aligned. To attempt to correct this, cross coupling of sensor information was attempted. This in turn though greatly complicated the circuit. This solution failed to work, most likely due to the sensor gain being too large. It was found that this caused parts of the circuit to stop functioning. Most notable is that once the sensor data is summed from the other sensors, the opamp on the power amplification stage can no longer maintain the “virtual earth”. The output in turn, will saturate and will no longer track changes in sensor data linearly.

The largest problem encountered from a control theory aspect was the side ways sliding of the levitating bar magnet. The six electromagnet system has the greatest chance of preventing this motion. It was found however that in the experiments with this system, the response of the electromagnets was too slow to stop the movement of the levitating bar magnet. By the time the electromagnets could react to the motion of the bar magnet, it had already slipped far enough from the ideal position to begin accelerating further from it.

Also problematic was the actual shape of the electromagnets. They are slightly difficult to set into various positions and to get them sufficiently close to one another. For this particular problem, the ideal was to get the end electromagnets into such a position that they could respond with the maximum repelling force to even the slightest movement in the levitating bar magnet.

8.5 LEVEL OF OPERATION

As stated above the current level of operation of the system has failed to achieve all the goals established in the beginning. The current system lacks the control circuitry required to achieve stable electromagnetic levitation.

At present, pairs of electromagnets can effectively levitate part of a bar magnet which is supported at one end. With careful positioning and arranging of a six electromagnet system, partial levitation can be obtained with only the sideways movement of the levitating bar magnet being physically restricted.

The individual parts of the system function well and as expected on their own. The basic system without any control is able to partially perform its intended function. As far as this is concerned, much was learnt and observed of the basic working of the overall system.

9. Recommendations

9.1 CURRENT CONTROL CIRCUITRY

Two designs were used during the development of this project. However, in the interests of quick construction, maintenance and modification, the initial one opamp design should be used. This circuit has performed as expected and would prove easier to work with especially as the system becomes more complex.

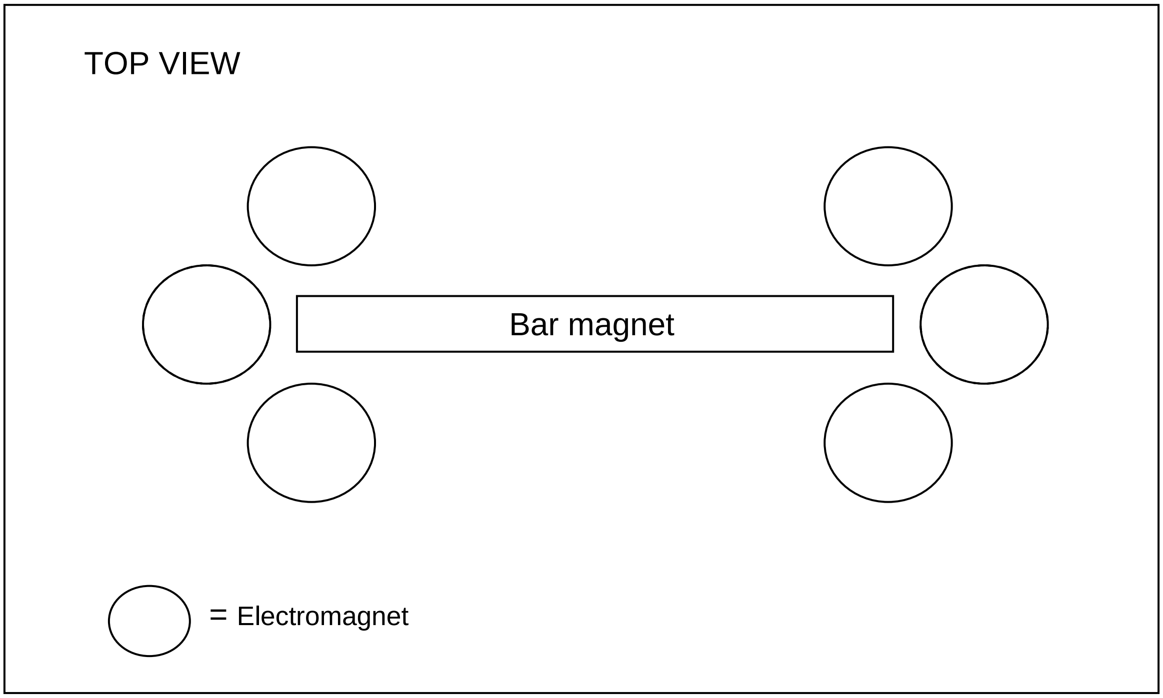
In the construction of the above system, separate circuits were constructed as electromagnets were added to the system. However, it may prove beneficial to add electromagnets (as necessary) in sets. Thus the circuitry can be accordingly constructed with dual and quad opamp IC packages. Even though the maximum supply voltage of these systems is ± 16V, the system designed in this project was more than able to perform levitation from a ± 15V supply.

To eliminate the complex transistor sink/source stage, the current control can also be done with power opamps. This may prove an alternate solution to the oscillation problem experienced in the earlier stages of construction of this thesis project.

Even though the circuit layout proved to be the least of the problems in the final model, it is none the less important to take this in to account. This would certainly prevent unwanted problems at the later stages of development.

9.2 ELECTROMAGNETS

From the experiments done, the minimum number of electromagnets required is six. Fewer electromagnets than this would lead to unnecessary complication of the final system, especially when control law is to be implemented. There are various arrangements that could be attempted; however, the following would prove the simplest to work with.



At test phase of design, this layout should be as flexible as possible. However, when a levitation test is initiated, care must be taken to firmly secure all electromagnets to make sure that they are unable to move.

9.3 CONTROL THEORY ASPECTS

The phase lead additions to the individual circuits performed well during the experiments. Further testing should be done though to examine more specifically what effect this addition has on the speed of response of the system. The main requirement from a control theory point of view is preventing the sideways motion that the levitating magnet is inclined to have in the current design.

The possible cause of this problem identified earlier was the slow response of the end electromagnets. These magnets were unable to react quickly enough to stop the levitating magnet from slipping off the end. These end magnets require a faster speed of response than the primary levitating magnets (the ones predominantly directly beneath the bar magnet). They also have to be able to produce a relatively large magnetic flux in reaction to a very small detected change in magnetic flux (caused by small movements of the levitating bar magnet). In other words, they must have a larger gain than the other magnetic levitation circuits.

This approach requires that an extensive analysis of the behaviour of this uncontrolled system be done. The exact behaviour of the system can then be used to determine the necessary control circuit required to effectively hold the levitating bar magnet in position above the electromagnet. There was also a slight side to side oscillation observed in the final stages of testing. Though this could be eliminated with a more accurate control over the positioning of the electromagnets, an additional failsafe should be added in the form of cross coupling of sensor data. By feeding position and speed information between the different electromagnet control circuits, a better more stable levitation can be achieved. The elimination of these control problems should ensure that a successful, working electromagnetic levitation model can be achieved.

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