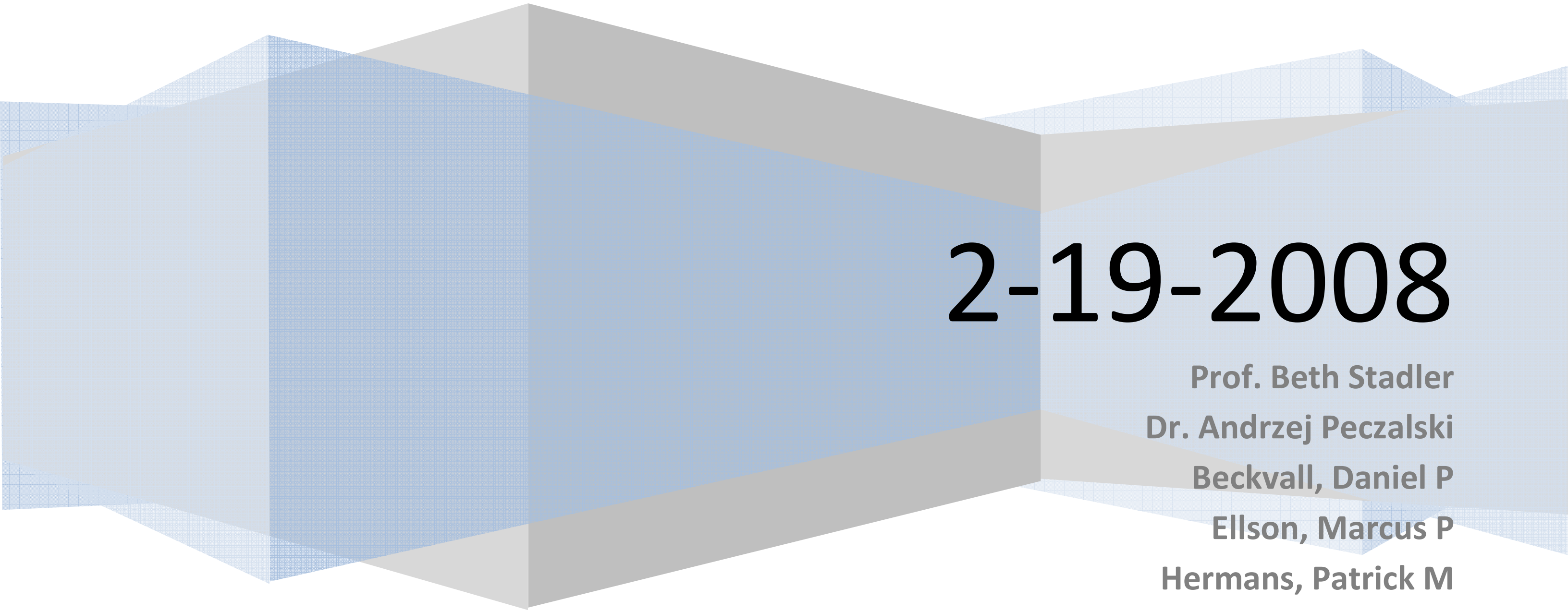
University of Minnesota

Magnetic Compass Design

Increasing Accuracy with Multiple Sensors



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Abstract

The purpose of the team's project is to increase the accuracy of a single AMR IC compass by using incorporating multiple ICs. The goal is to increase the accuracy of a magnetic sensor by the number of multiple ICs used. This will be done by obtaining data from within the linear regions of operation for each sensor and applying a weighted averaging algorithm. The team is required to completing the project by April 29, 2008. Sensors and test equipment will be provided by Honeywell and the University of Minnesota's Electrical Engineering Department.

Motivation & Background

Magnetic sensors are used in navigations systems, magnetic hard drives, proximity sensors, position sensors just to name a few areas of applications. With this said, it is becoming more and more important to minimize the size of such sensors while maintaining or increasing accuracy and resolution. A proposed method of decreasing sensor size is to use nanowire technology, which is many times smaller than the current IC sensors being produced. However, these individual nanowires are not very accurate. The question then becomes whether or not combining multiple nanowires together would boost accuracy to match or exceed current IC sensors while still being much smaller in overall size. With this being the motivation, it will be the group's task to determine whether multiple sensors can be combined to give a significant increase in accuracy and resolution.

Due to the fact that nanowire technology is still in its early stages and requires highly sophisticated equipment and procedures, the project can be simplified to a proof of concept using alternate sensors. With personal navigation becoming more and more in demand amongst today's consumers it has sparked the interest of many magnetic IC sensor companies to create chips for use in various types of compasses. For example, Honeywell manufactures several ICs with the sensitivity required to measure the earth's magnetic field and provide electronic developers with the ability to judge direction accurately. These magnetic and compass ICs are very small and fairy low cost which will work well for the group's proof of concept.

The goal of the team project is to combine many independent magnetic or compass ICs together to significantly increase the resulting accuracy and resolution. Since this is a proof of concept size, cost, power consumption, and the like are not important in the final product. It will then be assumed that the outcome of combining multiple ICs to increase accuracy will be the same for combining multiple nanowires in the future. If all goes well, this will have produced reasonable evidence and algorithms that combing multiple nanowires with low accuracy can be combined to create a highly accurate and small magnetic sensor solution.

Prior Work & Solutions

Since the project was proposed to us by Dr. Peczalski, there was no previous work for this specific project. To the best of the group's knowledge and research, no one has done any research on using multiple nanowires to increase the accuracy over a single nanowire. Furthermore, to the best of the group's knowledge no other devices current use multiple IC chips in various orientations to increase accuracy. However, within some IC sensors multiple magnetoresistive wheatstone bridges are used to broaden overall range and in some case increase accuracy. The extent of this while remaining coplanar has been limited to two bridges and therefore has not yet been fully explored as this project plans to do.

It is important, however, to have an understanding of how other digital compasses and similar navigation devices have been designed. Due to the fact that anisotropic magnetoresistive (AMR) sensors will be used for this test of concept the scope of this description will therefore, be limited to AMR sensors and those which use them.

AMR sensors measure the orientation of a magnetic field by means of a differential voltage that is produced by a wheatstone bridge configuration of four magnetoresistive elements. The wheatstone bridge is shown below in Figure 1.0, where the pink strips are the magnetoresistive elements, and the voltage measured across the center is the differential voltage produced.

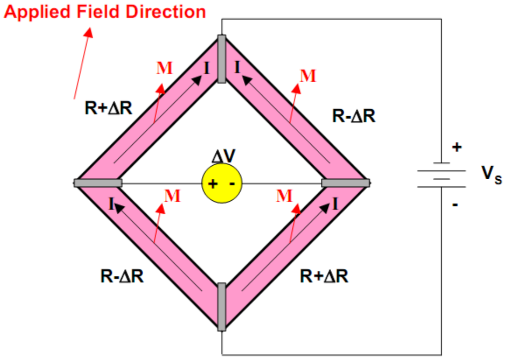


Figure 1.0: AMR Wheatstone Bridge

This configuration works to create a differential voltage that varies with respect to the direction of the applied magnetic field due to that fact that the resistive properties of the individual magnetoresistive elements change resulting in different voltage drops around the bridge. The output differential voltage as a function of the applied magnetic field direction with respect to the bridge orientation is shown below in Figure 2.0.

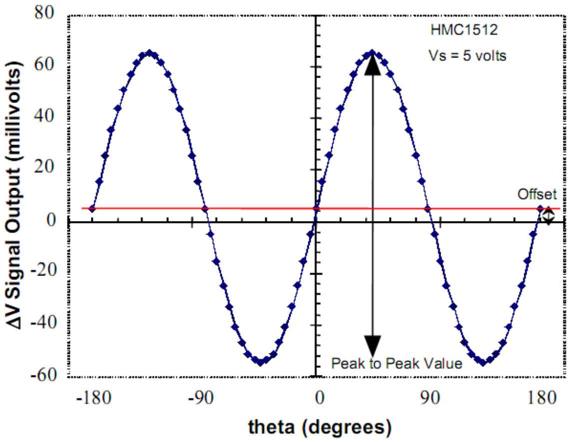


Figure 2.0: AMR Wheatstone Bridge Voltage Output

From Figure 2.0 above there are a few points of interest. First, it is important to note that there is a window from -45 degrees to +45 degrees before all output values are repeated. This means there is only a 90 degree window for which a magnetic field direction can be determined using only one bridge. It is also important to note that this function is not linear. This means that at some positions a small change in magnetic field direction will cause a large voltage change than at others. Obviously, where the voltage change is greatest for the smallest direction change the more accurate the sensor will be, this happens during the linear region shown from roughly -35 degrees to +35 degrees. These items of interest need to be taken into account when formulating a working compass and compensated for.

Other designs have compensated for the limited 90 degree range by introducing multiple bridges and Hall Effect sensors to specify which quadrant or hemisphere the measured magnetic field is within. As a bonus, this also easily increases accuracy by creating more linear regions which can be staggered to create effectively one continual linear range. Figure 3.0 below shows the plot of a device using two bridges positioned 90 degrees apart with an addition of a Hall Effect sensor.

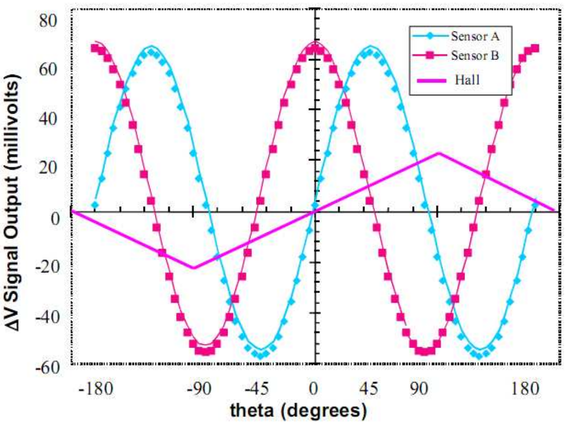


Figure 3.0: Dual Bridge with Hall Effect Sensor

Using Figure 3.0 above it can be seen that whenever sensor A or B is outside its linear region the other sensor has entered it linear region, always supplying a very accurate voltage reading. Furthermore, using the different signs from each of the bridge output and the hall effect sensor the resulting direction can be placed within the correct quadrant extending the range to a full 360 degrees.

To further increase the complexity of using these devices is the fact that the output voltages produced are fairly low, less than 1 volt. Therefore, amplification is generally required to allow for sufficient accuracy. This often posses an additional challenge because the amplifiers need to be tuned with great precision. Fortunately, this has been perfected and there are many devices available that will perform the amplification needed and many that also provide a digital output that can easily be interfaced to a microcontroller for processing.

Requirements & Specifications

The requirements for the final product are straight forward and simple. It should consist of two compasses or the equivalent, from which one will be composed of a single AMR sensor and the other of multiple identical AMR sensors. The specs for each compass should be determined accurately and identically for each device to be used for comparison purposes. Specifically, each compass should be tested for repeatability, precision, accuracy, and effective resolution with the goal to increase each by X fold, where X represents the number of chips used in the multiple chip compass design.

Because this project is a proof of concept there have been no restrictions on power consumption, overall size, budget, or likewise other than the need to stay within obvious safety boundaries and to use common sense. The only requirement is that the direction should be computed and displayed within a reasonable time frame, such as within approximately 1 second.

When the product has been completed and testing has been done to determine the specs for each compass and final conclusion should be made as to whether multiple sensors can significantly increase accuracy over an individual sensor. Furthermore, if the proof of concepts passes some thought should be done to determine if this concept will/should hold true for nanowire sensors in the future.

Proposed Design

Sensor Selection

The bulk of this design revolves around the AMR IC sensor selected. Andy has given us the choice to use any of three sensors made by Honeywell; the HMC1042l, the HMC105x series or the HMC6352. After many in-depth data sheet reviews and debates were placed over the conclusion was made to go with the HMC6352.

One of the main reasons the HMC6352 was selected by the team was its I2C capabilities. I2C is a communication protocol that allows you to communicate to multiple devices using their addresses as a way to distinguish one from another. In the case of the HMC6352, each chip can calculate its own heading, voltage readings, or (X Y) coordinate. This will allow us to greatly simplify the circuit. Without these capabilities the team would be forced to have many analog to digital conversions along with several operational amplifiers. The processing capabilities far outweigh its only foreseeable down side, its field range of measurement. It field range can measure B fields anywhere from .10 - .75 gauss. This is fine for applications such as navigation systems because the earth's magnetic field around this region (upper Midwest) is around .6 gauss. The only foreseeable problem is getting a constant B field to test in. If the team were using another sensor that can measure fields at ± 6 gauss the team could cancel out any of the earth's magnetic field with a stronger artificial B field created by winding coils.

The last reason that the HMC6352 was chosen was that its accuracy is a little less than the other available sensors. The HMC6352 is specs say that it is accurate to within 2.5 degrees. This is less accurate then the other sensors that are accurate within 1 degree. This is good because it will allow the team to see more definitive results. Although the team has a highly accurate rotational table that will allow for us to measure precision, other resources like a highly accurate directional gauss meter might be needed to see significant improvement in accuracy. With less accuracy the team will be able to answer the general question about using multiple sensors more definitively. With everything taken into account the team settled on picking the HMC6352 as the sensor that would be used in the final circuit.

Overview

Our proposed design is shown below as a block diagram layout in Figure 4.0. As can be seen, it consists of two separate boards connected by an 8 wire cable. The main board, on the right, contains the microcontroller that will be used to control the various devices and compute a direction to be displayed. Also on this board are all the peripherals the team feels are required to accurately gather data and troubleshoot any problems that may arise. The daughter board, located on the left, contains the array of AMR IC chips used to gather data about the direction of the applied magnetic field. It also contains other minimal hardware required to operate the IC's and a laser to precisely depict and set the orientation of the daughter board.

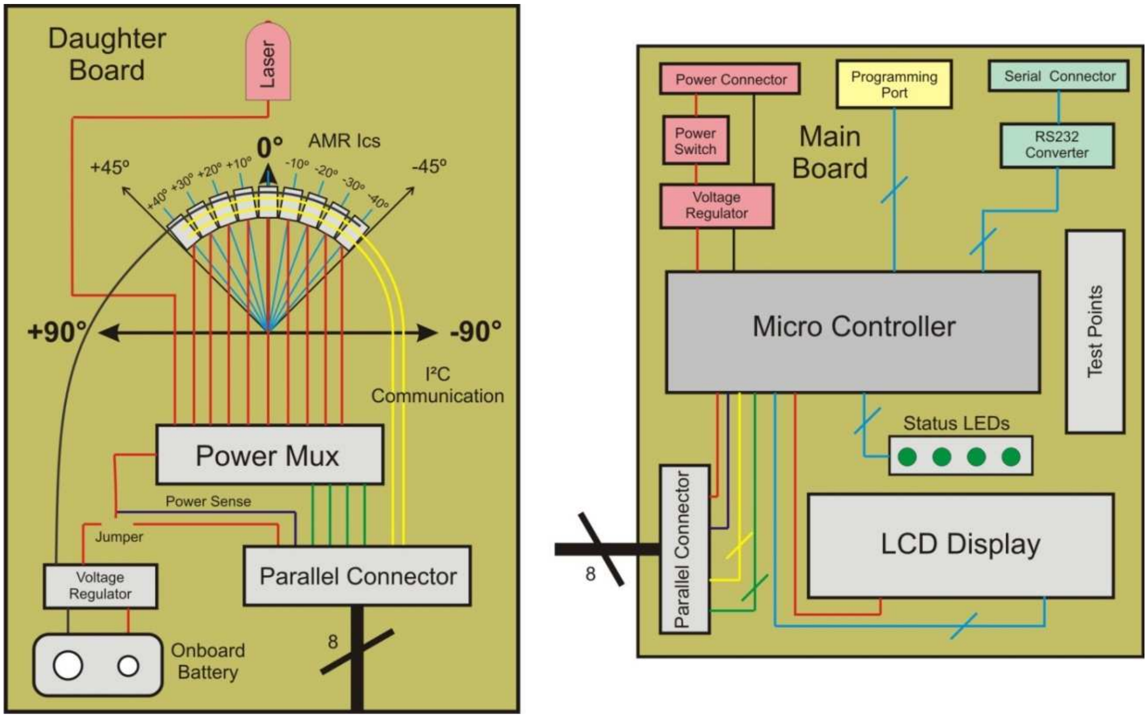
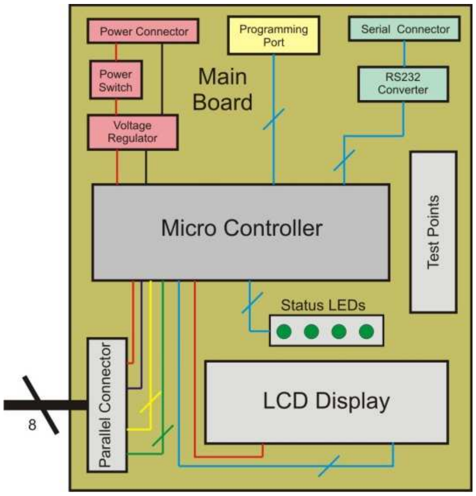


Figure 4.0: Proposed Block Diagram Layout

The board layout has been broken into two separate boards to serve multiple purposes. First, having the components on separate boards make each board smaller and less bulky. This will become very handy when it becomes time to mount the product to the rotation table for testing. Having the micro on one board the AMR IC's on the other will enable the Daughter Board to be remained mounted while the Main Board can be removed and have its flash updated or be modified. Separate boards also serve as a safety net. If one boards fails, or has been constructed wrong the entire project is not lost. As an added bonus if the desired orientation/layout of the AMR ICs is wished to be changed a new daughter board can simply be constructed. The design will also allow for variations in number of IC's as well as orientations without the reconstruction of the main board. Using two boards should also make the group's testing and configuration processes easier. Having the sensors on a separate smaller board will allow us more easily use reflow soldering on the sensor array which will help the sensors align more accurately to their PCB pads. Once the sensors are mounted to their board, the daughter board as a whole can be treated like and individual sensor which will allow for easier breadboard level testing and calibration.



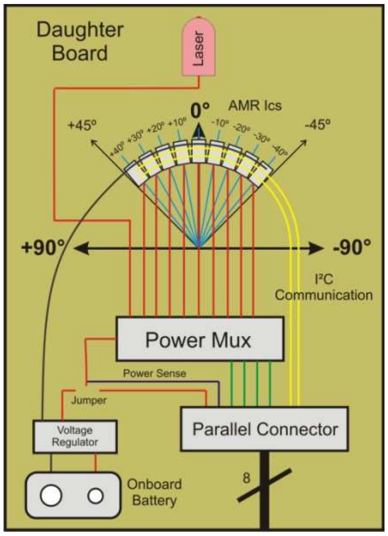
Main Board

The main board as shown to the right contains the all the equipments to control and collect data from the AMR ICs located on the daughter board. Great lengths have been taken to ensure that this board can handle everything required while at the same time be very versatile and adaptable in case something has been overlooked or requires a change.

The microcontroller is the key component to this board and the entire project. It is the work horse, and will be used to communicate over I^2C to the AMR ICs as well as to a computer running hyper terminal or LabVIEW via a serial connection. At the same time it will also be required to display pertinent data to the onboard LCD and status LEDs. To increase the usability of the board a built in programming port has been added along with an area to probe various control lines and pins for troubleshooting purposes.

The parallel connector will require a minimum of 11 data lines to be sent to the Daughter Board. They are as follows: 1 laser power, 1 for all ICs power switched via BJT,1 for the mux power, 1 to sense power voltage, 2 for I^2C, 4 (minimum) for the power mux control, and finally a ground connect. The uses for each of these connections will be discussed in a following section. It is important to note that the power mux is used to turn on individual ICs, therefore to support the addition of more ICs on the Daughter Board in the future, more mux lines will be required. For this purpose the labeled 11 data line will probably contain extra wires connected to the microcontroller not used in this configuration.

Daughter Board



The daughter board, shown at the right, contains the AMR ICs that will be used to determine the magnetic field direction with an onboard laser used to pin point the board direction from which to be calibrated. Along with these it contains its own optional power source and power mux control system.

Because the ICs communicate over I^2C they are all connected in series and need to be addressed individually when sending commands. The issue with this is that from the factory they all contain the same name address and there is no way of communicating to each one individually. The power mux allows each IC to be turned on individually in order to reprogramming the IC's name address such that when they are all turned on each one can be addressed individually. An added benefit to the power mux is that it minimizes the number of lines required to be connected to the micro controller. At the same time, many more ICs can be controlled with the addition of minimal mux control lines if future designs require such modifications.

It can be seen that the power mux also has two available sources. This has been done for multiple reasons. First, having all nine ICs powered by an output of the microcontroller will draw to much current for the mux and the microcontroller to handle. The power for when all ICs are on will be routed directly to the power source on the daughter board and connected by a BJT transistor via a line controlled from the microcontroller. This allows the board the flexibility to operate independently of the main board without worry of voltage drop across the connecting cable. As an additional feature, the parallel connector could also then be plugged into a wireless device, such as one using the ZIGBEE protocol, and be made completely separate from the mother board for uninterrupted orientation swings.

The placement of the individual IC sensors on this board are placed every 10 degrees between the interval of 0 to 90 degrees for a specific reason. Consider the following diagram shown below in Figure 5.0 where 9 sensors are laid out 10 degrees apart.

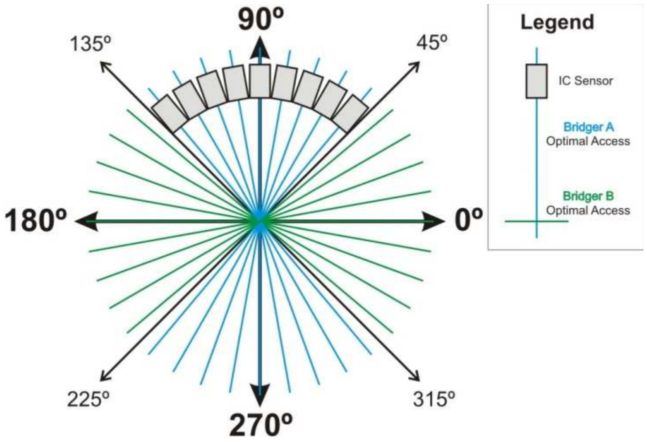


Figure 5.0: Optimal Axis's for AMR IC Sensors Spaced 10 Degrees Apart

If the AMR IC has two wheatstone bridges inside rotated by 90 degrees from each then they will have two optimal axes where the magnetic field direction reading will be most linear and accurate. These two axes are shown in Figure 5.0 by the blue and green lines for each IC, as also indicated by the legend. As can be seen rotating the IC by 10 degrees provides the smallest interval between consecutive optimal axes while remaining uniform and without doubling up in any one place throughout a full 360 degrees. The same can be concluded for the orientation shown below in Figure 6.0 where the chips are spaced every 20 degrees apart.

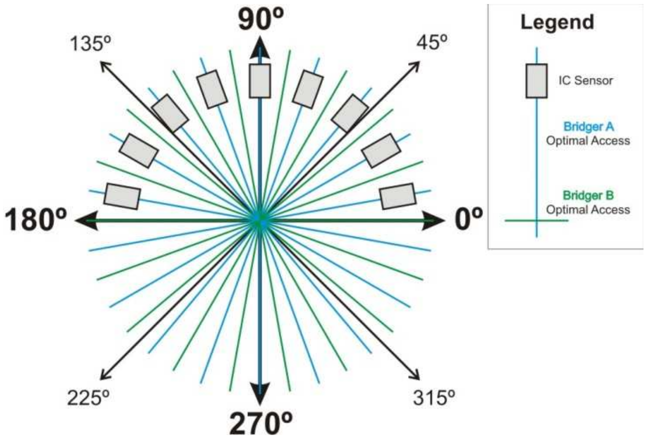


Figure 6.0: Optimal Axis's for AMR IC Sensors Spaced 20 Degrees Apart

Both of these orientations should provide the same data and however, in the second case the optimal axes alternate between a bridge A (blue) and a bridge B (green) where as in the first case there are nine consecutive bridges A optimal axes followed by nine bridge B axes before repeating.

How It All Works

The two boards shown above will be used to simulate both a single AMR IC sensor compass as well as a multiple AMR IC compass. This will be done in software by only requesting one sensors data or all sensors data and performing similar analysis on each the retrieved data. The results will be done simultaneously (or consecutively) and display side by side on the LCD display and possibly transmitted to the a computer via the serial connection.

The entire product operates on a fairly simple concept. Use as many sensor as possible orientated such that there optimal, most linear, most accurate regions of measurement are spaced evenly about a 360 degree area. A magnetic field is then applied to the device and the sensor measuring within their reasonably linear and accurate region will be polled by the microcontroller and the direction measured saved. The measurements can then be combined and averaged to make a more accurate reading than an individual IC could do on its own. Currently, the thought is to weight each sensor's measured value based on how close it is to measuring from within its optimal axis and then perform an average of their readings. The measurements can then be repeated and averages together over multiple readings before outputting a final value to remove any noise and obtain the best measurement possible. Multiple algorithms for performing this have been discussed and are currently in the process of being coded into a Matlab simulation for analysis.

Setup & Configuration

With the current Main Board proposal setup will be extremely streamlined and easy. The built in programmer will allow the microcontroller to be securely fastened to the board and never need to be removed, removing the risk of breaking pins. It can be programmed on board and then tested and reprogrammed at will. This will allow quick and fast code modifications, changes, or updates through testing and final demonstration if need be.

As hinted at previously, setup consists of being able to address each IC sensor individually over I^2C. Due to the fact that each sensor is set to the same address name from the factory, if they are all connected in series and powered on they cannot be communicated with individually. To solve this problem a 1 to 16 MUX has been incorporated onto the Daughter Board and used to power each sensor individually. With the ability to power each sensor individually they can then one by one be powered on and given assigned a new unique address name from which to be communicated with from that point on. After each IC sensor has been give an address they will then be powered by the external power source connecting all of them together and controlled by a BJT transistor controlled by the microcontroller because the mux cannot handle enough current to feed all the ICs at once.

Data Acquisition & Computation

Retrieving measurements from the AMR ICs will be relatively easy. The current plan involves addressing a single IC over I^2C and retrieving its raw X and Y bridge voltage differentials. These data will be saved and then the next IC sensor will be called and the process repeated until all sensors have been called. From this point the data can either be analyzed, but if time permits a it would be beneficial to quickly gather three sets of raw data from each sensor to be averaged to remove noise and jitter.

From the non-averaged, or averaged (if applicable) raw data mathematical operations will be performed to determine to overall magnetic field direction. The data for a single IC sensor will first be analyzed to determine the most accurate possible direction by means of checking which of the two on board wheatstone bridges are most within its linear range and making a weighted average. The result will then be saved and send the LCD screen. Once the single IC direction has computed, the saved raw data from all the chips will be combined in a similar fashion and the result displayed to the LCD screen next to the single IC result. The process will then be repeated until the device is shut down.

Meeting Requirements

In order to meet the remainder of the requirements stated above, testing procedures need to be determined to compute the specs for both the individual IC and multiple IC compass readings. The following test plan describes preliminary ideas as how to determine accuracy, precision, and repeatability.

Accuracy

Definition: Accuracy is most easily understood and is usually reported as maximum possible difference from the true value. In the team’s case with a compass it can be expressed as how near to the true reading does it point, example +-5 degrees.

Plan: A firm plan has yet to be determined to compute the accuracy of the team’s device. In order to do so the team needs an instrument with greater accuracy than the team’s device. Future talks with Andy should determine what device the team can use. Once a higher accuracy piece of equipment is obtained it can be compared with that of the group’s laser pointer output which can be sent a significant distance and broadcast on a wall where any minute error will be amplified.

Precision

Definition: Precision can be defined as the smallest unit increment a product can measure. For example, if the team's compass is rotate a known 10.0 degrees, and the compass readout changes by 10.1 degrees it could be said to have a precision of 0.1 degrees. This is different form accuracy in the sense that it may have a very precise reading, lets say within tenths of a degrees, but may have a large offset representing bad accuracy.

Plan:

1. Create a uniform field in the correct range for the group's sensors using the Hemholtz Coils.

2. Using a laptop/LabVIEW interface to the High Precision Rotary Table the team can get a precision angular reading for when the device reads 0° 0' 0" or some other recordable value.

3. Rotate the table, again very precisely, and compare the known change in the table to the change in the team's devices output.

4. The device can output a reading calculated from the 9 sensors and also a reading from a single sensor for comparison.

Repeatability

Definition: Repeatability may seem as if it is a function of accuracy and precision but it is not. The best way to describe this is with an example. Assume the compass at hand has an accuracy of +-5 degrees and a precision of 0.1 degrees. Now assume that when positioned at 0 degrees the compass reads 4.1 degrees, very inaccurate but with moderate precision. Now rotate the compass around and then place it again facing 0 degrees. If the compass were to now read 4.2 degrees it would have good repeatability of 0.1 degrees, if it now read 2.1 degrees it would have bad repeatability, of 2 degrees.

Plan:

1. Create a uniform field in the correct range for the team's sensors using the Hemholtz Coils.

2. Using a laptop/LabVIEW interface to the High Precision Rotary Table the team can get a precision angular reading for when the device reads 0° 0' 0" or some other recordable value.

3. Take a reading from the constructed compass.

4. Rotate the table around to multiple positions. Wait a little bit and then return the table, again very precisely, to the previous position

5. Take another reading from the constructed device.

6. Compare the readings. If the readings are the same the device is very accurate.

7. The device can output a reading calculated from the 9 sensors and also a reading from a single sensor for comparison.

Conclusion

Once the specifications have be determined a conclusion can be made. If the the proof of concepts passes a little research into the area of nanowires should indicate whether the same setup should significantly increasing accuracy with nanowires. Specifically, one might want to see if they have a linear and non linear region of measurement like the AMR ICs do, as this is basis of the group's averaging routine.

Budget

If the sensors are provided by Honeywell the team's simple circuit design will easily be within the department's 200 dollar price range. Beth Stadler and the Electrical Engineering Department will provide the team with the necessary testing equipment.

Conclusion

With this design the team hopes to get nine fold the accuracy of an individual sensor. If the original hypothesis is correct and more sensors can improve the accuracy then Honeywell might be inclined to look into adding more axes to their sensors or more sensors to their navigation systems. Research may also be done to begin implementation of nanowires into the wheatstone bridge in place of the currently used magnetoresistive elements to further decrease size.

Timeline

Key dates are listed below and are highlighted in gray on the gantt chart shown below in Figure 7.0.

- 2/19 Design Proposal Due
- 3/4 - 3/13 Engineering Design Reviews
- 4/1 In Class Poster Review
- 4/22 Executive Summaries Due
- 4/29 – 5/1 Product Launch Presentations
- 5/6 Poster Session
- 5/13 Final Report

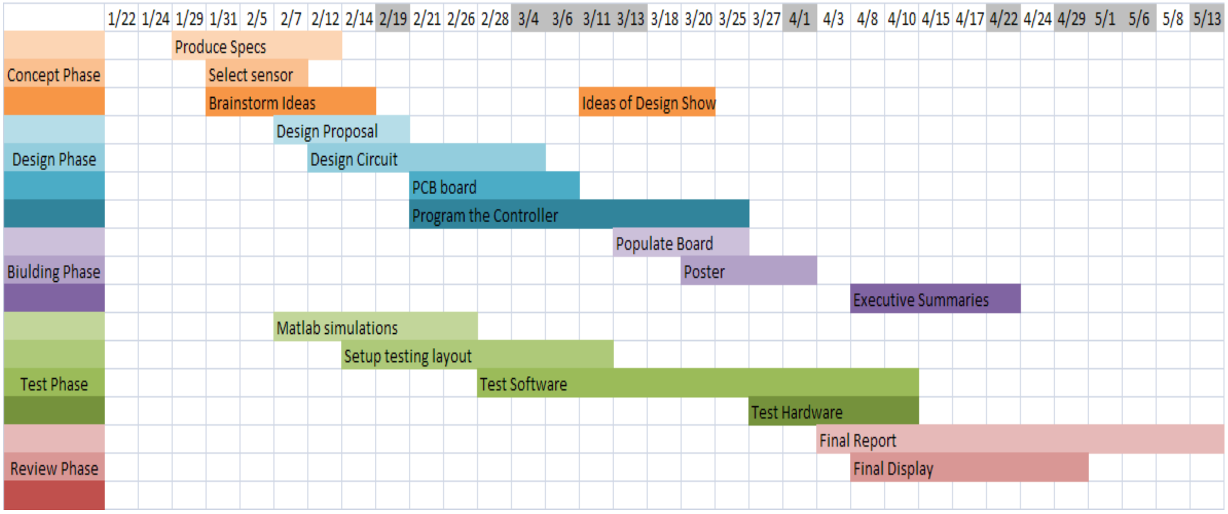


Figure 7.0: Project Gantt Chart

The bottleneck of this timeline is the printed circuit board. If the team falls behind in the PCB, the team will have to put population of the board on hold. This might delay hardware testing. It is very important that the team finishes and submit the board on time to prevent further missed deadlines.

Experience & Resources Available

Collectively, the team has much educational experience that is relative to the project. Each team member has learned about the properties of magnetism in the second physics course in the Institute of Technology curriculum, which is physical properties of electricity and magnetism. In addition, the team has also been educated in the core electrical engineering principles, such as linear electrical systems, analog electronics, digital design, and statistical methods in electrical engineering, which are not only important to understand how the sensors work, but also what is needed to design the hardware. T he junior design lab in the electrical engineering program also gave each team member an experience working with a small group on a semester long hardware design project. Finally, each team member has taken a unique combination of advanced electrical engineering courses, and several relevant examples are advanced digital design, embedded system design, control systems.

The team also has work experience that is relevant to the project that has been gained through internships and hobbies. These include software simulation of electronic hardware, electronic hardware design support and testing, and MEMS sensor data analysis and other data analysis with matlab software.

The team has been provided with sufficient resources to be successful. They have been given access to an electronics lab that has equipment such as power supplies, oscilloscopes, and digital multimeters that will aide in hardware testing. They also have access to a high precision rotary table and gaussmeter that will assist in hardware testing, as well as two large diameter Hemholtz Coils that will be needed to create a small EMF large uniform magnetic field to test and demonstrate the performance of the hardware.

There are also a number of software tools that will aide in the design and testing of the hardware and software. These include National Instruments' LabVIEW for recording and analyzing data, Mathworks' Matlab for simulating and analyzing data, Microchip's MPLab for software development, simulation, and testing, and Cadence's OrCAD for hardware design and simulation.

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Appendices

Data sheets

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