Ambulatory Blood Pressure Monitor Via Pulse Wave Transit Time

Final Report

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EXECUTIVE SUMMARY

The Halberg Chronobiology Center believes that blood pressure measurements over a one week period can be used to better prevent hypertension, kidney disease, retinopathy and other blood pressure related conditions. Blood pressure cycles change throughout the day, and week, are difficult to observe using traditional measurements. Current blood pressure measurements use a sphygmomanometer and are generally not taken often enough. The goal of the Phoenix Project is to develop an ambulatory blood pressure monitor that can be worn comfortably and record measurements for week-long durations. Medical professionals will be able to use this tool and data to develop better preventative and treatment techniques.

The Phoenix Project has been working to develop an open source blood pressure monitor through a volunteer basis and has completed much of the hardware development. The difficultly has been in developing a sensor technique that is not sensitive to movement artifacts. Movement artifacts are a disturbance caused by moving the appendage where the measurement areas are located. The current measurement technique involves elastic bands holding the piezoelectric sensors (movement) or IR arrays (reflected IR waves) close to the measurement surfaces. This form of attachment was uncomfortable over long periods of time. The blood pressure is derived from the blood pulse waveforms at two different locations that are different distances from the heart. Facing these problems a new approach was deemed necessary to meet the Halberg Chronobiology Center's requirements.

The design group's task was to develop sensor technology that can measure blood pressure unobtrusively, comfortably and without movement artifacts. The current Phoenix Project's solutions were determined to suffer from movement artifacts that caused a large disturbance to the output waveform destroying meaningful sensor readings. Filtering of the disturbance was attempted, but with limited results. The group chose to explore a new approach using magnetic sensors with a biasing magnet.

The magnetic sensor and biasing magnet allow the measurement of the blood pulse waveform from magnetic disturbances created in the blood pulse pressure wave. An advantage of this technique is the magnet and sensor do not need to contact the skin allowing padding to be placed between the PCB and the measurement area, thus improving comfort. Another advantage occurs when the sensor and the biasing magnet are held in space relative to one another. The group theorizes that this could reduce moment artifacts. Power consumption is also lower than the other prototypes because half the circuit, the magnet, does not require power.

A circuit was designed and verified by our group to measure the blood pulse waveform on the wrist with the magnet and sensor separate. The circuit and magnet were then mounted on a PCB board. The PCB holds the magnet and sensor relative to one another as stated above, however, no blood pulse waveforms were observed. Further work needs to be done to determine if the magnetic disturbance can be obtained with the magnet mounted on the PCB board.

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1. Introduction

1.1 Background

The goal of the Phoenix Project, a non-profit study group of the Twin Cities IEEE, is to create an inexpensive, unobtrusive, and easy to use ambulatory blood pressure monitor for the Halberg Chronobiology Center at the University of Minnesota. They hope to create a device that is comfortable enough for everyday use and can be worn for at least 7 days and require little previous knowledge on its structure in order to be used correctly. The final product will measure the pulse waveform at two separate locations on the body, at different distances from the heart, to determine blood pressure from the pulse transit time. Figure 1.1 shows an example of the delay observed in the pulse waveform when measuring at two different locations.

This non-intrusive measurement technique will provide a long term alternative to the current method of applying pressure via a cuff and obtaining measurements. This will allow medical professionals to view long term blood pressure readings that can help more accurately determine the overall health of the patient, and possibly discover issues that would otherwise have been missed. It has been shown that changes in blood pressure cycles allow a unique insight into the detection of common vascular variability disorders, such as hypertension, stroke, kidney disease, retinopathy and other health concerns [1]. The inflatable cuff used in blood pressure monitoring applies pressure, which frequently causes pain and is an unrealistic option for continuous use. The Phoenix Project hopes to solve these problems.

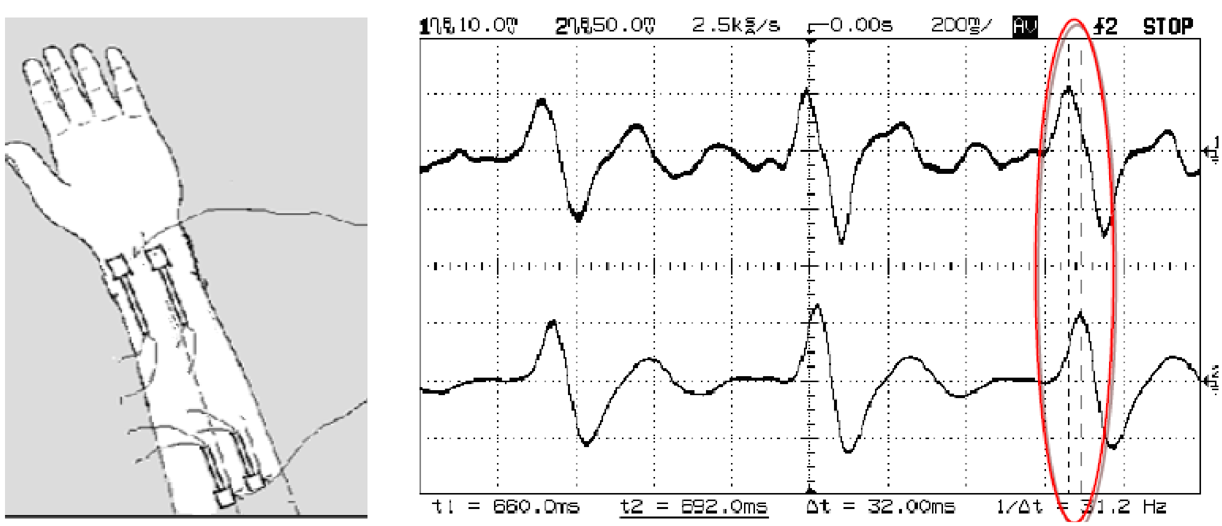

Figure 1.1: Observed delay in pulse waveform

The design team's goal was to improve on the existing designs used by the Phoenix Project. Expanding to the use of other sensor technologies, specifically magnetic and infrared, was the approach the design group chose to pursue. Our initial testing of the different sensors showed more promising characteristics than the currently used piezoelectric sensor. The initial analysis further focused the efforts of the design team to develop a solution using only the magnetic sensor.

1.2. Medical Motivation

This type of blood pressure monitoring is useful for all people as studies have suggested that a target blood pressure of 120 mm Hg on the average is better than a higher upper limit, which cannot be determined using by a single blood pressure reading [1]. Another benefit is that medication regiments for treating blood pressure related issues can be tailored not only to the individual, but also to the times that the issues occur. For example, if a week's worth of readings show that a person only has high blood pressure issues while sleeping at night, medication can be prescribed to be taken in the evening, and not during the day. Figure 1.2 shows the blood pressure readings of a 33 year old man, taken every half hour for a month. The dots on the graph indicate the individual blood pressure readings (in mmHg). Each vertical line of dots represents the readings taken from each day at the same time. From this we can see that the average blood pressure readings follow a sinusoidal pattern. It is possible to sample a higher or lower reading than the overall average blood pressure for a given time of day, but the average can be seen by continuous blood pressure monitoring and viewing all the available data.

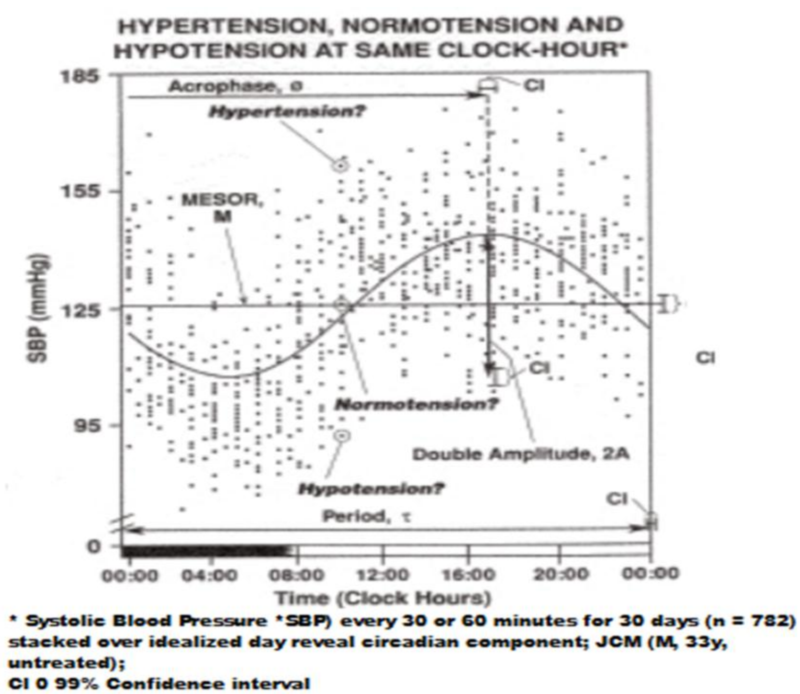

Figure 1.2: Blood pressure readings of a 33 year old man taken every half hour for a month.[1]

A condition known as overswinging or CHAT (circadian hyperamplitude-tension) is of concern [citation needed]. This is having too large a daily variation in blood pressure. Figure 1.3 shows what a normal blood pressure sinusoidal pattern might look like (on the left) and compared to the blood pressure readings of a person suffering from CHAT might look like (on the right). The person with CHAT would have wider fluctuating blood pressure readings. This causes the increased amplitude in the average blood pressure sinusoidal wave. This condition not only carries with it an increased risk of stroke, but also an increase in the risk of kidney disease.

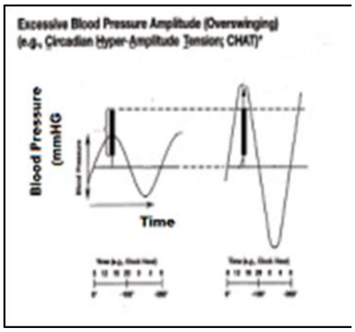

Figure 1.3: Overswing or CHAT(circadian hyperamplitude-tension)[1]

Although people with borderline hypertension are likely to gain the most from continual blood pressure monitoring, the benefits to all people can be pronounced. Only by continually monitoring blood pressure can we insure the best chance to catch possible issues, diagnose the problem, and work towards a solution. Continually monitoring will provide the earliest detection and the best chance at a positive resolution.

1.3. Customer Needs

The Phoenix Group requires a sensor technology and circuit that can provide a high quality blood pulse waveform. The details of the Phoenix Group's needs are discussed below with the most important needs appearing first.

(1) The sensor technology needs to be unaffected by motion artifacts. The final blood pressure monitor is intended to be worn 24/7 for at least a week. It is required that the measurements being recorded are not effected by motion artifacts while an individual is active, thus destroying valuable data.

(2) The pulse waveform needs to be clear of noise and needs to be as complete as possible. Any noise added to the waveform may skew the transit time calculation changing the blood pressure reading. The complete waveform requires that the "valley" be more visible allowing a more precise measurement of the diastolic blood pressure.

(3) The final device is required to be small and unobtrusive. The monitor is intended to be worn actively for at least a week. The small size of the device would improve comfort and would be concealable if privacy were a concern.

(4) Batteries will power the final blood pressure monitor. The microcontroller and recording circuitry will share the battery power. A low power sensor solution is critical if long measurement times are to be achieved.

(5) The sensor technology needs to be inexpensive. The motivation of the low price point is to have the device be available and used by individuals that may need to be screened. The final device is to cost less than $100.

1.4. Product Design Specifications

The Phoenix Project required the final blood pressure monitor meet several criteria, the most immediate criteria was listed in the above section. The design group developed a set of specifications to address these needs and appear in the same order. A numbering scheme was added for clarity in relating the design specification to the Phoenix Project needs.

(1) The sensor chosen will be required to have a readable blood pulse waveform while the measurement area is in motion. Addition filtering or post-process frequency domain analysis can be used to remove artifacts if possible.

(2) The completed prototype is required to have a signal-to-noise ratio of at least 10:1, though ratios are desired.

(3) The final prototype is required to be less than 2”x4” and not more than ¾” in height. This will allow for the prototype to be mounted and worn on an athletic sleeve. The sensor must occupy a space less than $8in^2$ using traditional through hole prototyping methods. The area required will be reduced if surface mount prototyping is used. The weight of the sensor will be less than 4oz.

(4) The final sensor design is to use components that have the ability to run at low voltages (i.e. 3.3V) or have low power equivalent components. Having the sensor run on battery power was viewed as a stretch goal. Prototyping was to be down with normal capacity components.

(5) A budget of $40 dollars is not to be exceeded in the final sensor prototype. This excludes the PCB design and is considering only the components needed for operation. This is not to include a microcontroller for additional filtering.

2. Design

2.1. Concept Development

The Phoenix Project's blood pressure monitor requires the acquisition of pulse waveforms at two different locations, different distances from the heart, to determine the pulse transit time. The blood pressure calculation is described in US Patent No. 6,599,251 and developed by Chen et. al and the primary equation is shown below. In the equation 'a' and 'b' are constants that are determined for each individual, 'T' is the arterial pulse time delay and 'P' is pressure.

$$P = a + b * \ln(T)$$

The task of the design group was to determine the best way to obtain a high quality pulse waveform. The design group contacted Larry Beaty (IEEE Phoenix Group and project advisor) early in the semester and we were provided with the design group's recommendations from the previous semester. They stated that the sensitivity to motion artifacts may be a fundamental problem with the piezoelectric sensors and recommended different sensor technologies. Infrared and magnetic sensors were mentioned though they acknowledged that some amount of research would be required to determine their viability of these solutions.

The design group researched infrared and magnetic sensors that were being used to measure pulse waveforms. There were several papers where a research group was exploring magnetic sensors in this way. An inexpensive GMR sensor and a biasing magnet was all that was required [2]. The sensor, a NVE Corp AAH02-002, was readily available and biasing magnets were obtained from a magnet vender. The circuit design in the paper was simple and the waveforms reported compared well to a standard pulse waveform shown in Figure 1.4.

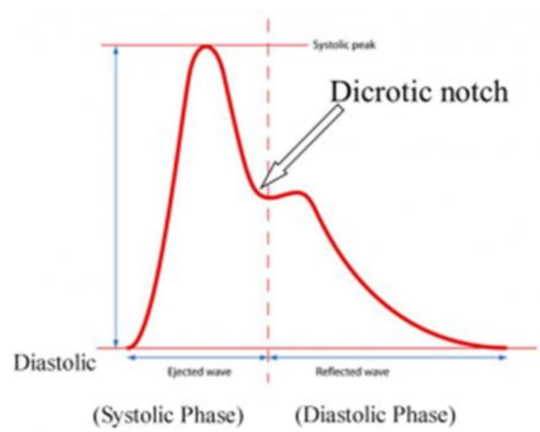

Figure 1.4: Standard Pulse Waveform

The project was split into two phases. The first phase was a feasibility study to compare the available sensors. The second phase was to further research the most promising sensor technology based on a set of criteria we developed. A list of sensor criteria was developed to be used in the selection of a sensor to be used in the final prototype.

List of Sensor Criteria:

1. Signal strength - How strong of a signal does the sensor output, how strong of an amplification of the signal will be necessary?

2. Size of sensor itself - Is the sensor small enough that can be worn comfortably?

3. Side effect on health that may arise by wearing it for a long time. - Are there medical implications to wearing magnets or infrared emitters for an extended period of time?

4. Ease of working with the sensors. - Can the sensors be easily placed in locations that provide a strong, useable signal?

5. Cost - Is the sensor inexpensive enough to fulfill the groups $40 sensor + amplification cost goal?

6. Noise/Disturbance - Is the sensor too sensitive to external sources of signal noise? How does the sensor react to motion of the measurement area.

7. Accuracy and stability of the waveform. - Can the sensor provide a useable steady waveform?

8. Ability to reproduce waveform from person to person. - Can the sensor provide good signals from all subjects?

9. Placement of sensor - direction, orientation, etc... - Will the placement of the sensor be an issue? Is it shaped oddly or have leads in a way that minimizes usefulness?

10. Need for extra leads and components that would complicate design and take up space. - Will the necessary leads and components make it overly difficult to reach our design objectives?

11. Pressure on skin needed to get pulse waveform. - Will the sensor require such physical pressure on the subject to get a good signal as to be uncomfortable to wear for an extended period of time?

The results of the sensor study are summarized in Table A in the appendix. The results were color coded and assigned a value that was summed. Based on this value the group compared sensors and it was found that magnetic and infrared sensors were equivalent.

Figure 2.1: Block diagram of blood pressure monitor

2.2. Description

The primary focus of the design group is to develop a sensor and amplification circuit shown in the block diagram in Figure 2.1. A GMR sensor utilizing a magnet biasing field was chosen as a sensor technology. The biasing magnet was a small, button sized rare-earth magnet. A LT1167 instrumentation amplifier was used for an amplification circuit. The DAQ was a NI USB-6009 used with a laptop running LabVIEW used for viewing and recording data. An Agilent oscilloscope was also used with a laptop to record waveform bitmaps and raw data. A standard laboratory power supply was used to power the design.

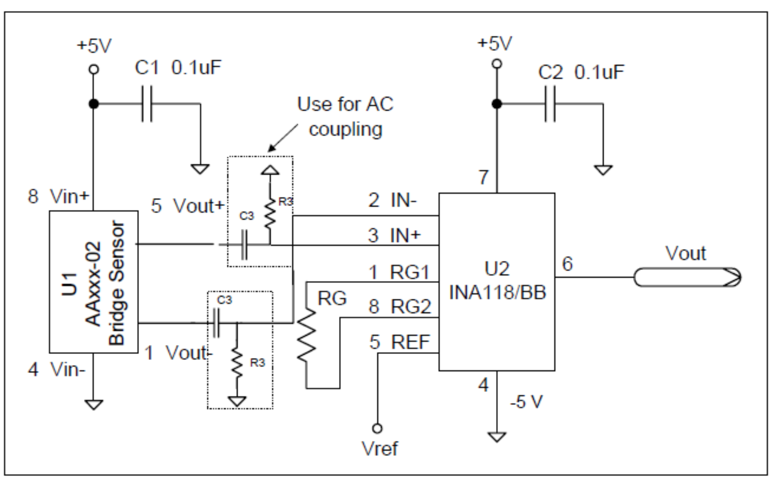

Figure 2.2: Recommended prototype circuit

Figure 2.3: Image of final prototype

The design of the magnetic sensor board required that the GMR sensor and biasing magnet be fixed relative to one another. A 1”x3” piece of fiberglass protoboard was used and the magnet and GMR sensor were attached with tape for the initial prototype. The prototype circuit can be seen in Figure 2.2 taken from the AAH002-02 data sheet. The final design had all the components mounted on a single PCB requiring an external power supply. The final design contained voltage regulators which provided a stable power source considering that a 4' cable connected the prototype to the power supply. The final prototype design and PCB layout are in the appendix. The completed final prototype can be seen in Figure 2.3.

The design works by utilizing giant magnetoresistance properties within the sensor, internally arranged in a Wheatstone bridge [3], such that voltages are read proportional to changes in the magnetic field. A magnet is used to provide a biasing field; the magnetic disturbances caused by blood flowing in this field will be detected by the GMR sensor. Output from the GMR sensor is taken to the instrumentation amplifier with a gain of 50, and then outputted to an oscilloscope or to the NI DAQ and LabVIEW. Filtering can be done by the oscilloscope or in post processing using MatLAB if a filter circuit is not used.

3. Design Evaluation

3.1. Prototyping and Results from Prototypes

The first phase of the project was to determine which sensor technology would developed further in the project's second phase. Three sensor technologies studies were conducted to determine which gave the best results based on the design criteria. The piezoelectric sensor and infrared sensor prototypes were already available and being investigated by the Phoenix Group. The magnetic sensing technique was mentioned by the previous design group and our group decided to develop a prototype after some initial research [2]. The first phase of the project is discussed below.

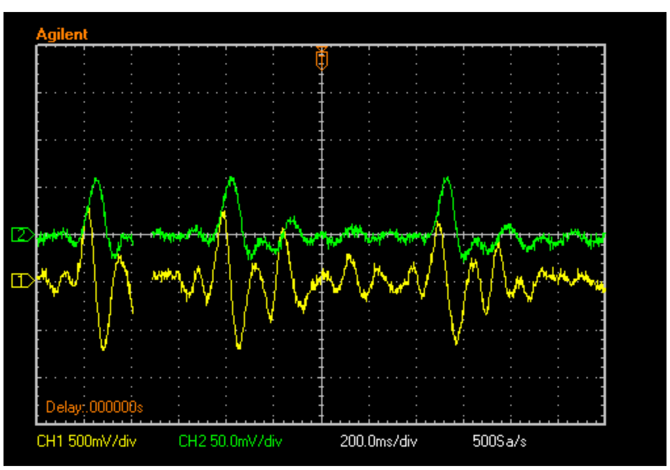

Figure 3.1: Piezoelectric sensor waveforms obtained

The piezoelectric sensor prototype used was made available by the Phoenix Group. The components used were two piezoelectric sensors, two amplifiers and an oscilloscope. The two sensors were attached to the arm at the wrist and the cubital fossa using elastic bands. The sensor at the wrist was placed over the radial artery and the sensor at the cubital fossa was placed over the brachial artery. The two sensors were approximately 9 inches apart. Two waveforms were viewed on a standard oscilloscope from the output of each amplifier box shown in Figure 3.1. A small time difference, on the order of 10-20ms, can be observed between the peaks of the two waveforms. This pulse transit time can be used to determine blood pressure if some constants are determined.

The results of the piezoelectric sensor study showed the limitations of the technology used. The oscilloscope was limited in its ability to obtain the data for analysis as either a bitmap image or the raw data could be download, but not both. Downloaded the data did not update the screen and therefore it was difficult to determine if a meaningful waveform was recorded. A computer with LabVIEW and a NI DAQ were also available to view waveforms; however the process was not streamlined due to the limited time allowed for the sensor study.

Working with the piezoelectric sensor demonstrated the problem of motion artifacts being introduced and destructing the pulse waveform. The smallest movement from the individual being measured, an example being small adjustment of the arm, would cause the signal to become unusable. It was noted that breathing caused the signal to have artifacts introduced. The design specifications called for the removal of these movement artifacts. The design group chose to explore other sensor technologies that could be less susceptible to movement artifacts.

The Phoenix Group had an infrared prototype that was tested. The IR emitter was a GaAs diode and the detector was a phototransistor. The emitter and detector were placed in close proximity and black tape was used to isolate the sensor/detector from outside disturbances. A transistor circuit was used for amplification of the phototransistor output. The sensor/detector array was placed on the radial artery with slight pressure being applied by an elastic band. The measured waveform is shown in Figure 3.2. A signal from the cubital fossa area was not obtained due to complications with the circuit and limited time allowed for prototyping.

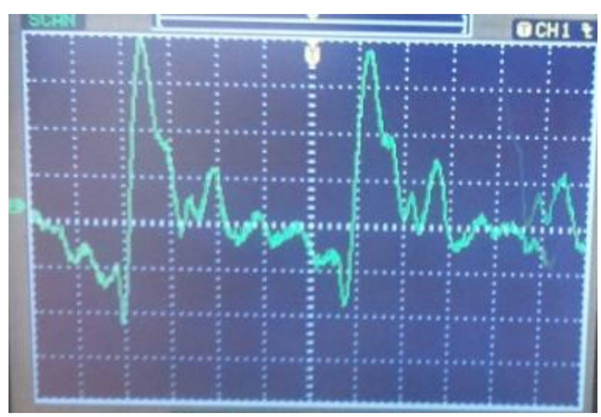

Figure 3.2: Infrared waveform obtained

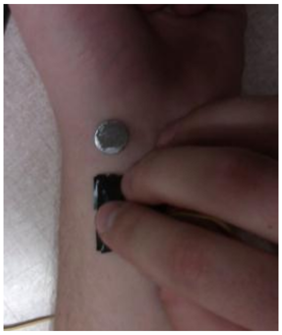

Figure 3.3: Measurement technique

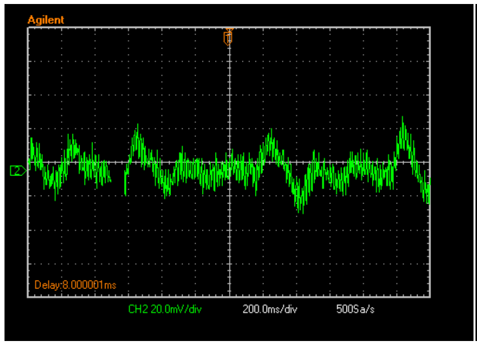

Figure 3.4a: Unfiltered waveform

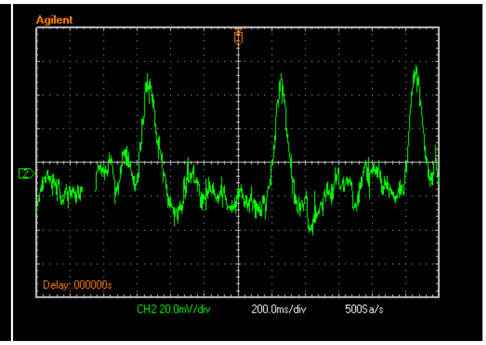

Figure 3.4b: Active low-pass filter

The limited operation of the prototype allowed for only a few observations. The major positive was a noticeable reduction in the movement artifacts that were observed from the piezoelectric sensors. A group member was able to move his hand while observing a clear waveform. It was noted that when the arm was inverted, the radial artery and sensor in the direction of the ground, the signal was lost. The cause was not clearly determined, but it is speculated the radial artery and sensor went out of alignment.

The magnet sensor prototype was developed by the design team. A small GMR sensor was obtained and attached to an adaptor for surface mount parts. A small button-sized biasing magnet was placed above the radial artery and the GMR sensor board was aligned approximately 3cm away, also above the radial artery as shown in Figure 3.3. An instrumentation amplifier was used with a gain of 50 and the output was viewed on an oscilloscope. Figure 3.4a demonstrates the unfiltered waveform and Figure 3.4b demonstrates a waveform with an active low-pass filter removing some 60Hz noise.

The magnetic sensor and prototype yielded a signal that could be obtained by multiple group members during different lab meetings. The sensor and biasing magnet were separate entities in this phase of the project and small movements of the measurement area created movement artifacts. It was speculated that mounting the magnet and sensor on a fixed base would eliminate the movement artifacts. The magnetic sensor was briefly tested at the cubital fossa, but no pulse waveforms were observed. Our group determined that the magnetic sensor was operating as expected, but the exact placement of the sensor and biasing magnet were important to the operation.

The conclusions drawn from the first phase of the project were that magnetic and infrared sensing technologies may prove to operate without movement artifacts. Infrared and magnetic were comparable when viewed through the sensor criteria used by the design group. Overall the decision to move forward with magnetic sensing was made due to the technology not requiring direct contact with

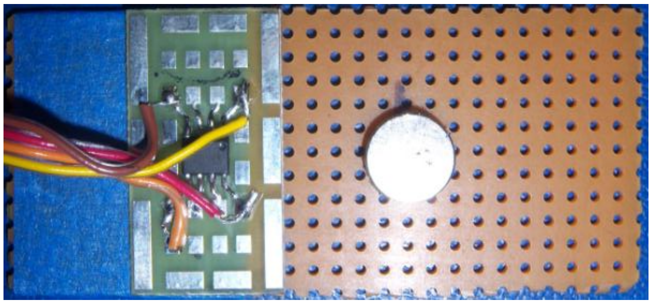

Figure3.5: Inital magnetic prototype

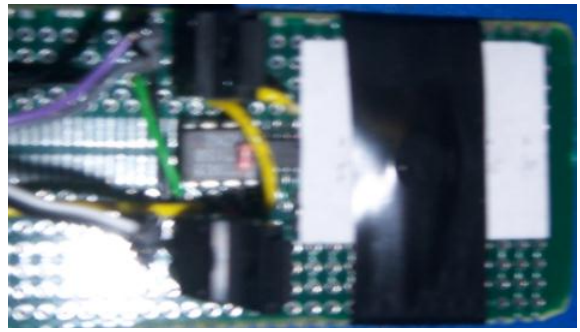

Figure 3.6: Second magnetic prototype

the skin on the measurement area. The second phase of the project began with the testing of a new prototype where the magnetic sensor and biasing magnet were mounted on a solid base. The magnetic sensor and biasing magnet being held fixed relative to each other was expected to remove movement artifacts. It was also expected that a pulse waveform would be measureable with the sensor and biasing magnet 1-2cm above the skin.

A prototype was constructed on a 1”x3” solid fiberglass base. The magnetic sensor was taped to one end of the base and the biasing magnet was attached with double sided tape approximately 2.5cms away from the sensor as shown in Figure 3.5. The sensor was wired to a solderless breadboard where an instrumentation amplifier and low-pass filter circuit were located. The output of the filter was attached to an oscilloscope. The same magnet, the same sensor orientation and same relative distances were used and the prototype was placed on the wrist above the radial artery.

The prototype, in this arrangement, was unable to detect the blood pulse waveform. The prototype was verified to be working by removing the sensor and biasing magnet from the fiberglass base and placing them on the wrist as described above in which a pulse waveform was observed. Different distances between the biasing magnet and the sensor were tried, but no results were obtained. Experiments were performed with different strength magnets and the sensor was tried in different orientations also yielding no results.

Another prototype was developed that placed 5V voltage regulators and the instrumentation amplifier on the sensor board to eliminate any noise that could be picked up on the cable between the sensor board and the power supply (Figure 3.6). Filtering was done by the oscilloscope by setting a low-pass filter at 10Hz. The instrumentation amplifier gain was set to 50. The sensor board was placed on the wrist over the radial artery. The magnetic sensor and biasing magnet components of the sensor board were aligned above the radial artery.

The new prototype was unable to obtain the waveforms that had been observed previously. Again, magnets of different strengths and sizes were used and different distances between the sensor and magnet were experimented with, but again there was no waveform observed. The prototype was determined to be working correctly due to an observed disturbance occurring when a large metal object or another magnet came near the sensor board. This was verified to occur on earlier prototypes.

The results for the second phase of the project are limited. It is speculated that the signal obtained in the first phase of the project, when the sensor and biasing magnet were separate entities, was due to the physical displacement of the biasing magnet moving on the surface of the skin above the radial artery. More research would have to be completed before conclusions can be drawn as to what the waveform observed was measuring. The design specifications were generally not met by the magnetic sensor. The primary goals set by the group, obtaining a clear pulse waveform and having a signal that was unaffected my movement artifacts, were not met with this magnetic sensor prototype. However, if the signal were to be observed, a small, unobtrusive sensor was developed. Also, if the signal were detected, low power instrumentation amplifiers and power analysis could have been conducted to determine how long the sensor could run off of batteries.

4. Conclusions

4.1. Summary of Results

The primary goals of the design team were to develop a sensor technique that would give the clearest pulse waveform readings and not be susceptible to motion artifacts. The ability to obtain a clear pulse waveform would allow for the most accurate pulse transit time measurements. Waveforms were obtained from all the sensor technologies tested and the design group chose to further develop

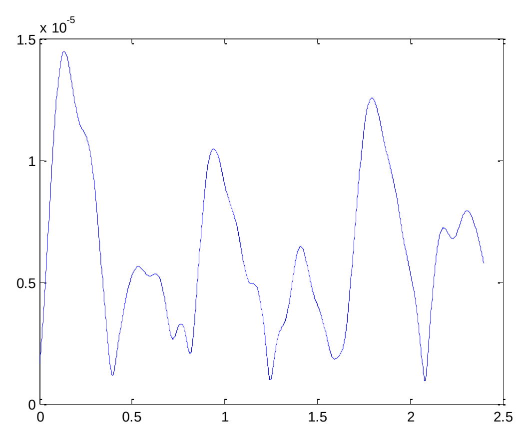

Figure 5.1: Magnetic sensor waveform with all frequencies above 10Hz removed

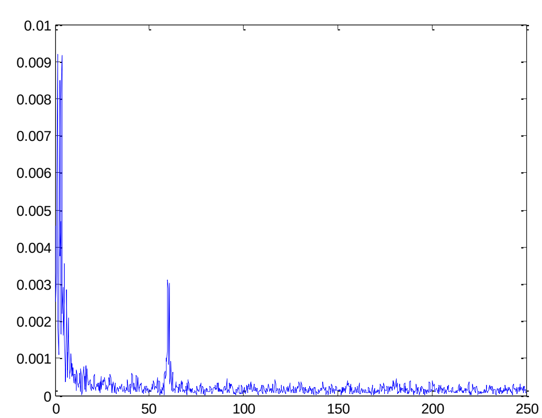

Figure 5.2: FFT of magnetic waveform

the magnetic sensor technique. The magnetic sensor waveform was observed as a periodic peak as seen in Figure 3.4b. Post processing was done on the collected waveform by removing all the frequencies above 10Hz resulting in the waveforms in Figure 5.1. The waveforms did not contain the "valley" of the blood pulse waveform. This may cause difficultly in accurately determining the diastolic blood pressure measurement compared to other methods due to the precise timing between "valleys". A FFT was performed on the filtered magnetic sensor waveform and a large spike at 60Hz can be seen in Figure 5.2. The major blood pressure frequencies are expected to exist below 10Hz.

Motion artifacts were observed in the prototype where the sensor and the magnet were separate and were on the order to those observed when using the piezoelectric sensor. The sensor and biasing magnet were mounted on solid base in an attempt to remove the motion artifacts and while doing so the previously observed pulse waveforms were no longer present. The inability of the new prototype to obtain a signal was a major challenge that we were not able to overcome.

The power the sensor technology could use was limited to power batteries could provide. Using a GMR sensor, which is a simple Wheat-stone bridge arrangement of resistors, and a low power instrumentation amplifier, a low power prototype could be developed while operating at 3.3V. However, due to the limited success with the design, no low power filters or instrumentation amplifiers were tested.

The cost of the magnetic sensor, biasing magnet and filtering circuit was less than $40 dollars. The limited budget for the sensor technology would allow the Phoenix group to have roughly the same budget for developing the microcontroller and recording circuits in the blood pressure monitor. The remaining budget would be used to produce a PCB that would contain the sensor and microcontroller circuitry. This goal was easily obtained due to the availability of inexpensive, on the order of $0.10, magnets and the low component count. The price could be reduced further by using more surface mount components.

The prototype was designed to be operated without skin contact while taking a measurement. This would allow for padding to be placed between the sensor and the skin increasing comfort and long-term wearability. A final product was viewed as being similar to an athletic sleeve with the sensors and circuit sealed inside. This goal was not tested due to the limited success of the prototype.

As discussed above, the strengths of the design were that the sensor was small and the final PCB used in the prototype measured approximately 1” x 3”. The design could be designed for low power and could run off of a battery if required. If the device were to operate as we had hoped, its size could have been worn comfortably. The major weakness of the final design is that a blood pulse waveform could not be obtained when the magnet and the sensor were mounted on a solid base together. When the sensor and magnet were analyzed as separate entities the system was susceptible to motion artifacts as seen with other sensor technologies.

4.2 Recommendations

As stated in an earlier section, having the sensor and biasing magnet as separate entities is not recommended because movement artifacts were observed with little relative motion between the two parts. When the sensor and biasing magnet were held in fixed positions on a solid base, no movement artifacts were observed, but pulse waveforms were not observed either. This occurred when using the same magnet and the same distance between the sensor and biasing magnet. More testing would have to be conducted with the prototype to verify whether or not the pulse waveform creates a magnetic disturbance strong enough to be detected. The current hypothesis is that the pulse pressure wave is actually physically moving the magnet, creating the signals that were observed.

The NVE Corp AAH02-002 GMR sensor was the only sensor explored in the magnetic sensor study. NVE Corp makes a large variety of GMR sensors that operate differently and have different sensitivities that could be explored. The AAH02-002 GMR sensor was chosen due to the frequency of it appearing in research [2][4] and the limited time allowed for conducting a sensor study. Computer analysis of how the blood and magnetic field interact could be explored [5]. This would allow for the expected signal size to be known and a better filter and amplifier strategy could be utilized.

The piezoelectric sensor technology is still a viable option if a sensor array and circuit could be developed to cancel out the common mode motion artifacts. This was option was pursued by a previous design group with limited success. As with the IR sensors, a method to couple the piezoelectric material to the skin would have to be developed that did not use elastic pressure. If a pulse waveform could be obtained from a sensor array that was insensitive to movement artifacts, it would have to be determined how susceptible the sensor is to environmental contaminates (i.e. dirt or oil).

Infrared sensor technologies were explored by this group, but for various reasons were not pursued. The Phoenix Group recently produced a PCB for an IR circuit that could be used for further testing. The most promising note from our IR analysis was the "valley" observed in the pulse waveform. This is a more complete waveform that could potentially give a more accurate diastolic blood pressure reading. Additionally, different IR sensors and emitters could be researched to determine if different wavelengths or sensor sizes/arrays would improve results. Methods to couple the IR sensor/detector to the skin could be explored that could improve the comfort level of wearing the sensor.

In our initial testing we observed the IR sensor was least susceptible to motion artifacts. Our group did enough research to understand the basics of how this sensor technology operates, but limited observations were recorded. Our design group strongly recommends the exploration of IR sensors.

4.3. Design Process

The design team had a clear understanding of the problem that we were tasked to solve because of the communication with the Phoenix Group early in the semester. The Phoenix Group allowed the flexibility to choose a different sensor technology if there was the possibility of better performance. The team discussed and came up with a list of criteria that the sensors were to be measured against using some the requirements of the Phoenix Group.

Much of the first half of the semester was spend researching and experimenting with the sensor technologies. The piezoelectric sensors were explored in the first weeks of the semester and the limitations of the design were observed while viewing the motion artifacts from even the slightest arm movement. The previous design group's work was examined and our group determined we try a fresh approach using either IR or magnetic sensor technologies based upon our initial testing. These solutions were viewed as being less susceptible to motion artifacts and therefore would require simpler hardware designs due to less filtering or not having to include a subtraction circuit.

A design of a magnetic sensor and biasing magnet mounted on a solid base was found while researching [4]. This design proposed that no motion artifacts would be observed if the measurement area was moved and that the solid base did not need to contact the surface of the skin. This design met most of the criteria set by the Phoenix Project and the design team.

A large amount of lab time was used trying to replicate the results of this paper, but in the end we were unable to do so. Testing of the prototype involved magnets of different strengths at varying distances from the sensor. An apparatus was developed that used metal filings suspended in a liquid to determine if the sensor could measure a magnetic disturbance from the fluid flowing through a tube. The sensor was determined to be a viable option, but more work would have to be done before conclusions can be drawn on the effectiveness of the magnetic sensor.

4.4. Budget

One of the goals of the Phoenix Project is to produce a prototype for under $100. The most expensive component of our design was the PCB which was ordered from Advanced Circuits at a cost of $33 plus a nominal shipping cost. The additional costs of passive circuit components were less than $10. The magnetic sensor was $12. Linear Technology provided free instrumentation amplifiers. Many different biasing magnets of different sizes and strengths were obtained at a cost of less than $10.

Part of our risk management was to order two PCBs from Advanced Circuits in the case where damage could occur to one of the prototypes during the build process or while testing. Also, additional magnetic sensors and instrumentation amplifiers were purchased and freely obtained during the project as backups during testing and prototyping. Having the extra components allowed for a one-day assembly of a prototype PCB without having to wait for additional parts to come in.

No budget was spent on equipment as was originally planned. The group had originally planned to allow $40 to explore each sensor technology, but no budget was spent on researching the IR or piezoelectric sensor technologies due to the Phoenix Group already having all of the components needed to do testing. The design project spent approximately $160 of the $300 dollar budget.

4.5. Timeline

The original timeline called for the first half of the semester to be a sensor technology study and the second half of the semester was going to be used to further pursue the most promising sensor. The prototype PCB was planned to be designed in late October after some final revisions of the initial test circuit. Final assembly was planned for the first weeks of December to be available for the Product Launch Presentation and Design Show. The original timeline was followed closely until there was difficulty obtaining a signal from the magnetic sensor when the sensor and biasing magnet were mounted and held relative to one another.

There was a discussion about shifting the sensor technology to infrared considering we had not committed very far into the magnetic sensor design process. It was agreed that magnetic sensor technology should be carried to a conclusion and any results, or lack of results, would benefit the Phoenix Project. During the time that we were unable to obtain a pulse waveform from the magnetic sensor work was done with filters and amplifiers to determine if the signal was present. Additional magnets of various strengths and shapes were also ordered taking more valuable time.

The PCB design was completed after the group decided to move ahead with the original prototype design where the sensor and biasing magnet were separate. The final design was several weeks behind schedule which, being a critical path, pushed the final prototyping back as well. The final prototype was not available for the Product Launch Presentation or the Design Show, but was completed the last lab meeting and yielded promising results with the magnet and sensor separate.

5. Acknowledgements

Our design group would like to thank the IEEE Phoenix Group, specifically Larry Beaty and Steven James, for answering our questions and helping us in the lab. We would also like to thank Prof. Salapaka for his feedback on the magnetic sensor testing. Final thanks for Prof. Ernie for conducting the course. The University of Minnesota and the Twin Cities IEEE chapter also deserve our thanks for the use of their equipment.

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Appendices

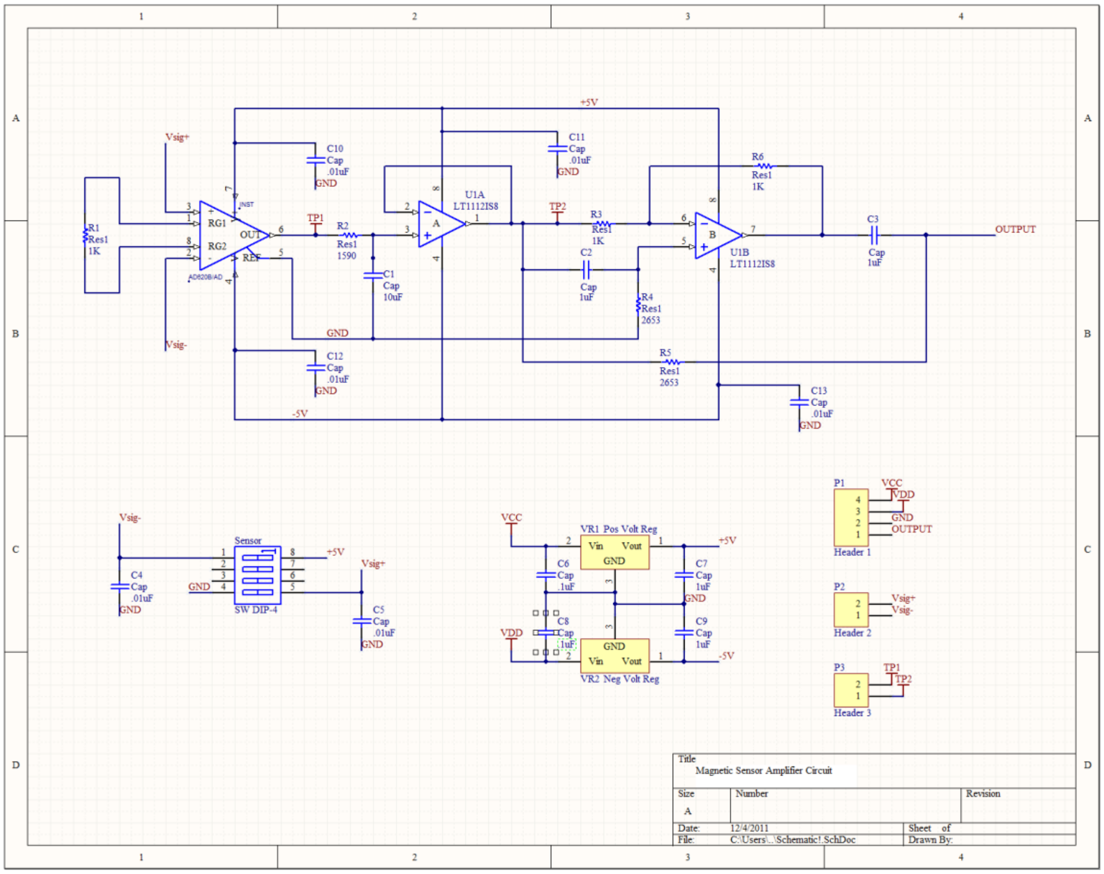


Figure A: Final prototype schematic (excluding GMR sensor)

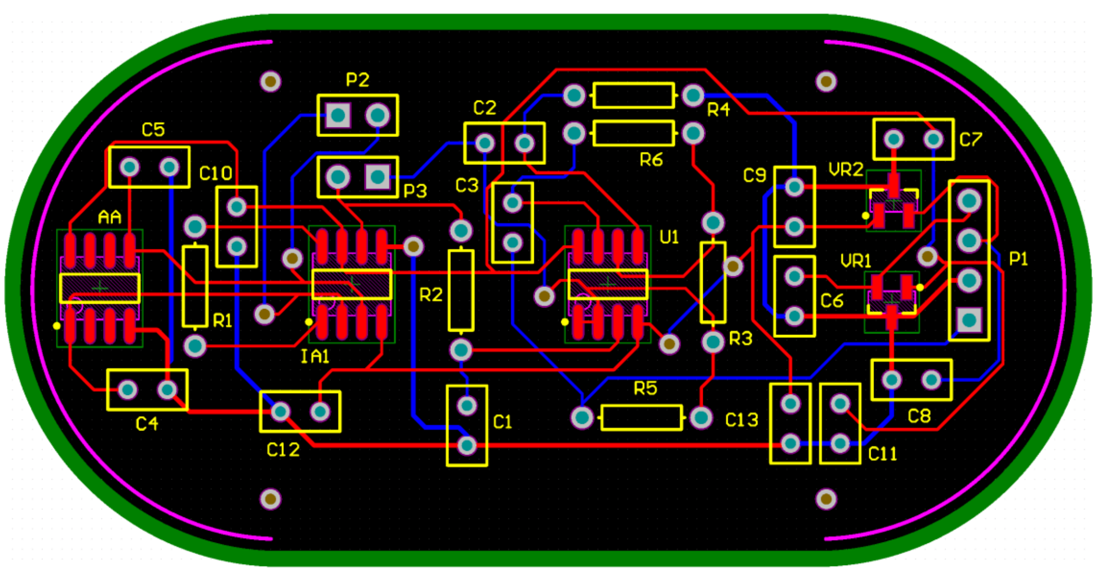


Figure B: Final prototype PCB layout

Table A: Results of sensor study follow chosen criteria

	List of Criterion	Magnetic Sensors	IR Sensors	piezoelectric Sensors
1	*Signal strength (output)*	60 mV/V at max field strength	Good output signal strength, up to 5V when touching, 18% at 0.2 inches	15-20 MV/µ strain (shows up well with provided amplifier)
2	*Size of sensor*	Smallest overall	Smallest single sensor, but need two.	Largest sensor by far.
3	*Side effect on health that may arise by wearing it for a long time*	None – Magnetic fields exist everywhere on earth.	Almost none – human emit infrared energy, dangerous in amounts far greater than we use.	None – sensor is encased in protective plastic film. Would have no more problems than any plastic bracelet
4	*Ease of working with the sensors*	Michael was able to get a reading but the rest of us struggled	Got a great reading the first time, haven't had luck since, possible issue with circuit.	Medium – Not too hard to find a signal (on the wrist at least), harder on the arm
5	*Cost*	$15.00 from NVE Corporation	$0.54 for an OP140D emitter and $0.57 for an OP550A sensor from Digikey	About $25 per sensor.
6	*Noise*	Unable to determine at this time. magnet and sensor were not mounted together for initial testing	Much less noisy than the piezoelectric sensors. Opening and closing of hand had almost no affect on the signal.	Very noisy, any movement at all, even breathing causes noise
7	*Accuracy and stability of the waveform*	Waveform was pretty stable, though hard to full judge without having magnet and sensor mounted. Accuracy looked about comprable to the piezoelectric.	Stability was better than peizo electric, withstanding movement better. Accuracy was better, looked closer the the expected wavefore for a pulse wave	Stability is not to bad, pulse to pulse looks good, if there is no movement. Accuracy is questionable, does not give any useable "valley" for diastolic blood pressure.
8	*Ability to reproduce waveform from person to person*	Only able to produce on one person so far, believed to be more of an issue with placement of manget vs. sensor.	Only tried on one person so far	Decent – not to hard to get a pulse waveform on different subjects.
9	*Placement of sensor - direction, orientation, etc*	Some difficutly finding correct spot. Did not try lined up orthogonally.	Sensors should be lined up in line with the artery. Did not try lined up orthogonally.	Placement must be directly on pulse point (artery). Orientation not a major factor.
10	*Need for extra leads and components that would complicate design and take up space*	Leads can be made short, design requires gap between magnet and sensor	Leads can be pretty short, just long enough to reach the output device.	Lead is attached and 18", no other need for lead.
11	*Pressure on skin needed to get pulse waveform*	None – The sensor does not actually even need to be touching the skin.	Moderate – too much pressure squishes arteries	Moderate – Pressure is not uncomfortable for a few minutes, long term unknown.
		23	23	22

Parts Information:

AA and AB-Series Analog Sensors

NVE's AA and AB-Series analog GMR sensors offer unique and unparalleled magnetic sensing capabilities. These sensors are characterized by high sensitivity to applied magnetic fields, excellent temperature stability, low power consumption, and small size. These characteristics make them suitable for use in a wide variety of applications from rugged industrial and automotive position, speed, and current sensors, to low-voltage, battery-powered sensors for use in hand-held instrumentation and implantable medical devices. The unmatched versatility of these basic magnetic sensors makes them an excellent choice for a wide range of analog sensing applications.

The AA-Series sensors use NVE's patented GMR materials and on-chip flux concentrators to provide a directionally sensitive output signal. These sensors are sensitive in one direction in the plane of the IC, with a cosine-scaled falloff in sensitivity as the sensor is rotated away from the sensitive direction. Also, these devices provide the same output for magnetic fields in the positive or negative direction along the axis of sensitivity (omnipolar output). All sensors are designed in a Wheatstone bridge configuration to provide temperature compensation. Two packages are offered, an SOIC8 and an MSOP8. These sensors are also available in die form on a special-order basis.

There are three families of NVE's basic AA-Series sensors: the standard AA-Series, the AAH-Series, and the AAL-Series. Each of these sensor families uses a different GMR material, with its own characteristics. The comparison table below summarizes the different characteristics of the GMR materials:

Parameter	AA Series	AAH Series	AAL Series
Sensitivity to Applied Fields	High	Very High	High
Field Range of Operation	High	Low	Medium
Hysteresis	Medium	High	Low
Temperature Range	High	Very High	Very High

The AB-Series sensors are differential sensor devices, or gradiometers, which take advantage of the high output characteristics of NVE's GMR materials. Two families of AB sensors are offered, the standard AB-Series and the ABH-Series. They have operational characteristics similar to the AA and AAH sensors described in the table above but with the bipolar linear output characteristics of a differential sensor.

Within these different sensor families, customers can find an excellent match to their analog sensor requirements.

Typhoon (Feat Chasing Shadows) -

LT1168

Low Power, Single Resistor Gain Programmable, Precision Instrumentation Amplifier

FEATURES

- **Supply Current: 530µA Max**
- **Meets IEC 1000-4-2 Level 4 (±15kV) ESD Tests with Two External 5k Resistors**
- **Single Gain Set Resistor: G = 1 to 10,000**
- **Gain Error: G = 10, 0.4% Max**
- **Input Offset Voltage Drift: 0.3µV/°C Max**
- Gain Nonlinearity: G = 10, 20ppm Max
- Input Offset Voltage: 40µV Max
- Input Bias Current: 250pA Max
- PSRR at A_V = 1: 103dB Min
- CMRR at A_V = 1: 90dB Min
- Wide Supply Range: ±2.3V to ±18V
- 1kHz Voltage Noise: $10nV/\sqrt{Hz}$
- 0.1Hz to 10Hz Noise: $0.28µV_{P-P}$
- Available in 8-Pin PDIP and SO Packages

APPLICATIONS

- Bridge Amplifiers
- Strain Gauge Amplifiers
- Thermocouple Amplifiers
- Differential to Single-Ended Converters
- Differential Voltage to Current Converters
- Data Acquisition
- Battery-Powered and Portable Equipment
- Medical Instrumentation
- Scales

DESCRIPTION

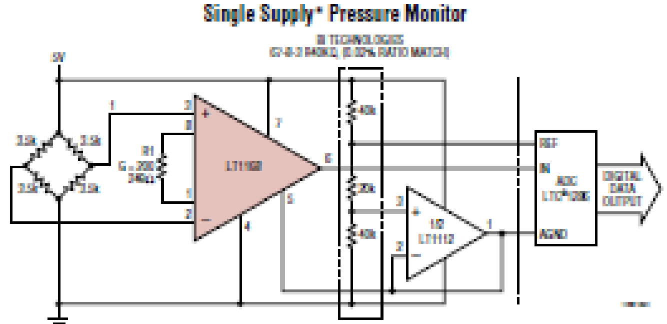
The LT®1168 is a micropower, precision instrumentation amplifier that requires only one external resistor to set gains of 1 to 10,000. The low voltage noise of $10nV/\sqrt{Hz}$ (at 1kHz) is not compromised by low power dissipation (350µA typical for ±15V supplies). The wide supply range of ±2.3V to ±18V allows the LT1168 to fit into a wide variety of industrial as well as battery-powered applications.

The high accuracy of the LT1168 is due to a 20ppm maximum nonlinearity and 0.4% max gain error (G = 10). Previous monolithic instrumentation amps cannot handle a 2k load resistor whereas the nonlinearity of the LT1168 is specified for loads as low as 2k. The LT1168 is laser trimmed for very low input offset voltage (40µV max), drift (0.3µV/°C), high CMRR (90dB, G = 1) and PSRR (103dB, G = 1). Low input bias currents of 250pA max are achieved with the use of superbeta processing. The output can handle capacitive loads up to 1000pF in any gain configuration while the inputs are ESD protected up to 13kV (human body). The LT1168 with two external 5k resistors passes the IEC 1000-4-2 level 4 specification.

The LT1168 is a pin-for-pin improved second source for the AD620 and INA118. The LT1168, offered in 8-pin PDIP and SO packages, requires significantly less PC board area than discrete op amp resistor designs. These advantages make the LT1168 the most cost effective solution for precision instrumentation amplifier applications.

TYPICAL APPLICATION

Single Supply* Pressure Monitor



*See Theory of Operation section

Gain Nonlinearity