Pediatric Dynamometer Using Piezoresistance Sensor

NSF Summer Undergraduate Fellowship in Sensor Technologies
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ABSTRACT

External forces on the body have long been known to have a large effect on children's bone growth and development. Researchers at Children's Hospital of Philadelphia (CHOP) want to explore this relationship. However, there is no current technology that directly measures the forces applied to the body. Dr. Babette Zemel, from CHOP, and Dr. Jay Zemel, from ESE at Univeristy of Pennsylvania, have been developing an in-shoe physical activity dynamometer (FootPAD), which will directly measure forces felt through children's feet. The past versions of this device have been developed using piezoelectric sensors; however, the drift caused by temperature changes in the shoe was unacceptable. This study looked into using piezoresistance sensors in the device instead of the piezoelectric ones. Preliminary tests with the sensors showed that they did not have the same temperature problem and that the sensors could accurately measure changes in force within the 10% accuracy needed. A circuit for the device using these sensors was designed and built, however further work with the software is needed before the device can be fully implemented and tested.

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1. INTRODUCTION

According to a 1995 study by Riggs and Melton, bone disease causes fractures in approximately 1.5 million people each year. However, as the US population is growing older this number continues to increase.[1] The surgeon general’s report on Bone Health and Osteoporosis predicts that by 2020 over half of Americans over 50 will be at risk of developing osteoporosis. Considering the increasing toll on the population, it is important to find the best way to prevent bone disease. Bone diseases decrease bone strength and increases fracture risk by impacting bone density, bone turnover, and bone structure.[2] Childhood is the primary time when bone is produced, making this age group the best focus for bone growth and development studies.[3] The stronger bones children develop the less risk of bone disease they face in the future.

A widely accepted model for the study of bone growth is the mechanostat theory, which predicts that bone size and mass will be impacted predictably by varying muscle force during growth. Studies of this effect have looked primarily at the correlation between exercise and bone development.[4] These studies have shown the importance of childhood exercise for strong bones throughout life.[3] However, it is difficult to directly measure the force of muscle on bone let along directly measure externally applied forces over time in humans. An example of the research needed is what aspect of applied forces has the greatest impact on bone growth and development, i.e is it the peak force, the total force, or the rate of loading that is important? With this information, researchers could develop an exercise regimen that could best improve bone strength.

Most studies have relied on parent and or child surveys, muscle measurement, or accelerometers to get information about the external forces experienced by the child.[4] However, survey data is problematic because it is subjective, and outside of extreme activity or inactivity it is difficult to get any accurate information about the intensity of activity. In addition, surveys provide little information about the actual external forces. Accelerometers are a valuable tool when looking at amount of activity. However, they are not capable of measuring static forces and do not take into account the force that would be added from carrying an object.[5] Many of these problems could be addressed by a pediatric dynamometer, which would be inconspicuous, e.g. in a child’s shoe, and be able to continuously collect data about the forces applied to the user's feet and legs. This would address many of the previous technology problems and the data collected could examine what part of the force has the most impact on bone development.

2. BACKGROUND

Since 2004, SUNFEST fellows and University of Pennsylvania students have worked with Dr. Jay Zemel to develop a pediatric dynamometer. [6] The original design fit inside a child’s shoe and was able to collect and store data over a reasonable period of time. However, the device used sensors of polyvinylidene fluoride (PVDF), a piezoelectric polymer film that produces a current proportional to the strain along the horizontal axis when the film is bent. However, it was not possible to get reproducible measurements with this sensor due an inconstant conversion from strain to the vertical force. A SUNFEST fellow in 2009 tried using a different type of piezorelectric sensor from Emfit Ltd. called a piezoelectret.[6] The electret principle uses dipoles induced across small air voids to generate a current when a vertical force compresses the dipoles in the air voids. Although these sensors were able to get reproducible measurements at a constant temperature, the sensor was temperature sensitive, causing a drift in the results that was unacceptable. To overcome this problem a less thermally sensitive sensor based on a “pressure sensitive ink” was selected to measure the force, the FlexiForce A201 force sensors shown in Fig. 1.[8] The FlexiForce A201 conductance changes linearly with the applied force (F). The linearity simplifies determining the force from a calibration since F = k(1/R), where k is a constant and R is the measured resistance.

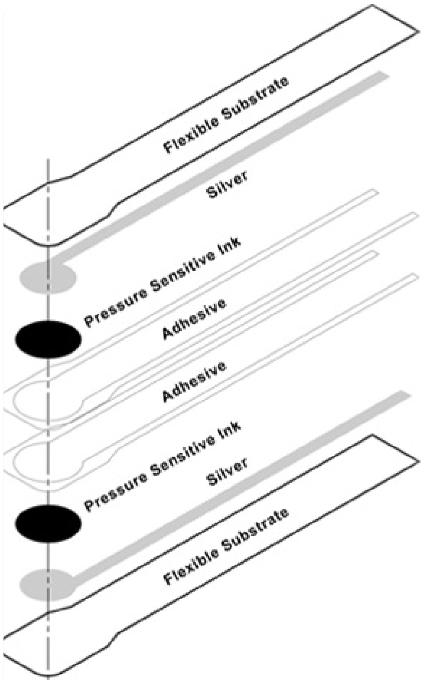

Figure 1: Construction of FlexiForce© A201 sensor. [8]

3. GOALS

The pediatric dynamometer is to be used by Dr. Babette Zemel, the Director of the Nutrition and Growth Laboratory at the Children’s Hospital of Philadelphia, to study the impact of forces through the feet on child bone development. In order to directly measure the external forces on children’s bones, a portable unobtrusive device that measures force needs to be developed. The pediatric dynamometer must fit inside a child’s shoe, accurately measure the force, and collect and store the data over a reasonable period of time. The data are communicated to a computer using a standard RS232 cable when the measurement period is completed. Past projects have been able to create a device that was able to do all of these except accurately measure the force. In order for the device to work with the FlexiForce A201 sensors, the analog section of the device has to be redesigned. The goals for redesigning the device are as follows:

Modify the existing user interface to work with the new system.
Build a working circuit that is as small as possible.
Modify the existing microprocessor program to take the necessary data and relay it to the computer.
Calibrate the sensor.

4. DESIGN AND BUILD OF THE PEDIATRIC DYNAMOMETER

4.1 Device Overview

The device consists of consists of a dual operational amplifier chip, the OPA2237, a Reg710 3V voltage stabilizer, a PIC 18F14K50 microprocessor, and a Numonyx M25P16 flash memory. A schematic of the circuit can be seen in Appendix A. The switch from the piezoelectric to the FlexiForce A201 sensor required a different signal coupling circuit. The PIX 18F14K50 microprocessor controlled the operation, timing of the measurements, data acquisition and transfer, etc., as well as converted the analog signals from the two op amps to digital format. The Numonyx memory chip stored the digitized data on board the device until read-out. These components were selected to match those used in another device developed at Penn, the Neonur. This device measures pressure changes in a baby bottle.[9] Although the purpose of the Neonur is different from the FootPAD, the underlying circuitry using the microprocessor and memory chip is the same.

4.2 Basics of FlexiForce A201 Sensors

The FlexiForce sensor is composed of two layers of silver connected to pressure-sensitive ink. This pressure-sensitive ink is only in the circular end of the sensor, so this is the only area where force is sensed in the device. The pressure-sensitive ink acts as a variable resistor, while the silver layers extend to connectors that can plug into the device. The resistance varies linearly with the applied force and since $V = IR$, so does the voltage. Once the proportionality constant is found this can be used to calculate force as
$F=kV/I$.

Figure 2 FlexiForce sensor used in device.[8]

4.3 Circuit Design

One of the goals of the project was to make the circuit as small as possible, however for testing a larger circuit was needed. The smaller circuit, which measures 1.23 in x 1.56 in, is shown in Appendix B. The larger circuit, shown in Appendix C, has wires attached at some of the vias to allow for easier testing.

4.3.1 Gain Circuit

The gain circuits for both sensors are set up as non-inverting amplifiers. Considering the variable sensor resistance as R_S and the load resistor as R_L the voltage in to the amplifier (V_m) is

$$\frac{R_L}{R_L + R_S} * 3V$$

(1). The load resistor keeps the current drawn from the battery to a minimum. The value for R_L was decided by testing the gain circuit on a breadboard across a range of forces at varying resistances. The resistance of R_L=1000∧ was determined to be the highest resistance with a reliable output, drawing only 3mA of current.

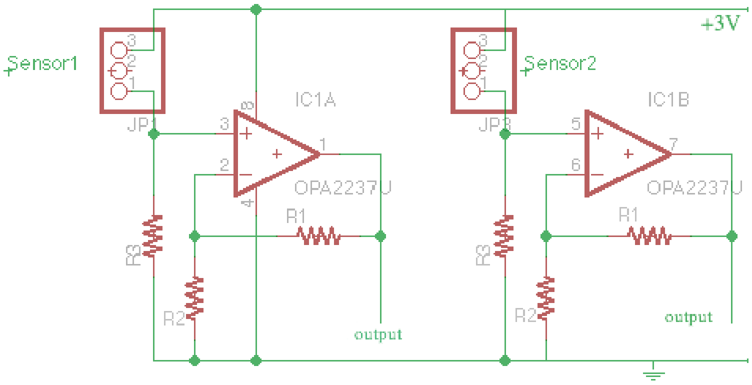

Figure 3 Gain circuit used in device

A non-inverting operational amplifier configuration gives the equation

$$V_o = \left(\frac{R_1}{R_2} + 1\right)V_m$$

(2). The microprocessor has an 8bit processing unit, meaning that it can operate with numbers up to 2^8 = 256. For the best resolution we want this to be equivalent to close to 2.56V. Based on data taken with the breadboard circuit without amplification, a gain of 17 was needed. This means that

$$\frac{R_1}{R_2} = 16$$

. Based on the resistors at hand, R_1 = 2430∧ and R_2 = 150∧, giving a gain of 17.2. Saturation of the operational amplifier is not a concern because the same voltage input, 3V, to the sensor is used in the amplifier and the output has been set up to stay below 2.56V.

4.3.2 Voltage Stabilizer

A voltage stabilizer is critical for accurate results from the device. As seen in the equation 1, the voltage output (what is recorded from the sensor) is dependant on V_{in}. As the battery is drained V_{in} would decrease, causing a drift in the results. The voltage stabilizer prevents this drift from happening. Texas Instrument's Reg710 3V was chosen for the part. This allows for the battery to go down to 2.8V[10] and still produce a 3V input to the rest of the circuit. In addition this device works with as little as 10mA current.

4.3.3 Microcontroller and Flash Memory

The Microchip PIC18F14K50 is the microcontroller used in the FootPAD. This chip employs software generated with the MPLAB and the C18 compiler. This software, distributed by Microchip, enables software to be written in C for the device rather than the more difficult-to-understand machine code that microchips use.

In addition to having analog-to-digital conversion capabilities, the PIC18F14K50 can communicate with the computer via the RS-232 protocol. The RS-232 cable used allows the device to interface with the computer using a USB connection rather than a serial connection. To make the pins line up appropriately between the USB cable and the board, a connector as shown in Figure 4 is used to switch the pins. Also, the serial peripheral interface (SPI) mode enables 8bits of data to be transferred to and received from the flash memory simultaneously. Both the flash memory and microprocessor can run on single supply voltage and draw little current, thereby extending the battery life of the device.

4.3.4 Constructing the Board

The circuit board was cut using a new LPKF Promat® S62 circuit board plotter. This machine was new to the University. Therefore, a protocol was developed to take a design from an EAGLE plot to a cut board ready to be soldered. In order convert an EAGLE file to a finished board; a set of jobs was first created to export the correct files from EAGLE to be used in Circuit CAM. A procedure was then developed to import these files into Circuit CAM, create the correct paths for the machine to follow when cutting out the board, and export the file to the machine operational software, BoardMaster. The last part of the protocol is used to import the paths to BoardMaster and cut out the board with this program. Although the machine is more automatic than the previous version used, many quirks needed to be worked out before the board could be successfully cut.

Once the board was cut, the components were then soldered on the board. However, due to the small size it was difficult to solder all of the components without creating a short circuit. Each component was checked and sometimes multiple versions of the board were made to ensure the connections were made correctly. The completed board is shown in Figure 4 with USB cable connector and a quarter for scale.

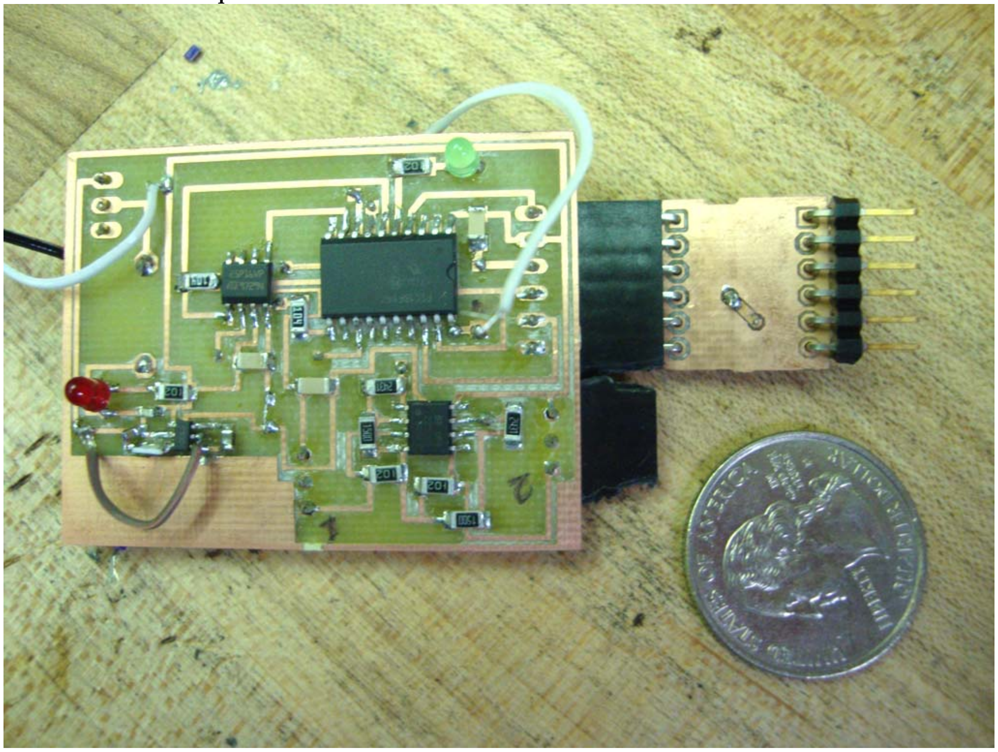

Figure 4 Finished circuit board.

4.4 Microcontroller programming

The programming used in this device is the same as that used in the Neonur.[9]

5. TESTING

Thus far we have not been able to get the fully implemented circuit to work consistently, so much of the testing has been done using a breadboard. With the breadboard circuit the voltage output from the amplifier could be directly measured, bypassing the need for any of the other components of the circuit design.

5.1 Verification of FlexiForce A201 Sensor Viability

Before the sensor could be implemented as part of the device, we needed to verify that it met the conditions needed. First, the sensor needed to be able to accurately measure force. Second, the sensor needed to not drift with changes in temperature at least between room temperature and around body temperature.

5.1.1 Accuracy

For the FlexiForce A201 sensor to accurately measure force it needed to have a consistent relationship between the voltage output and the applied force. According to the manufacturer, there should be a linear relationship between force and voltage output. To test this the voltage output was measured at varying forces. The force was measured using a scale and the voltage output was measured using a voltmeter.

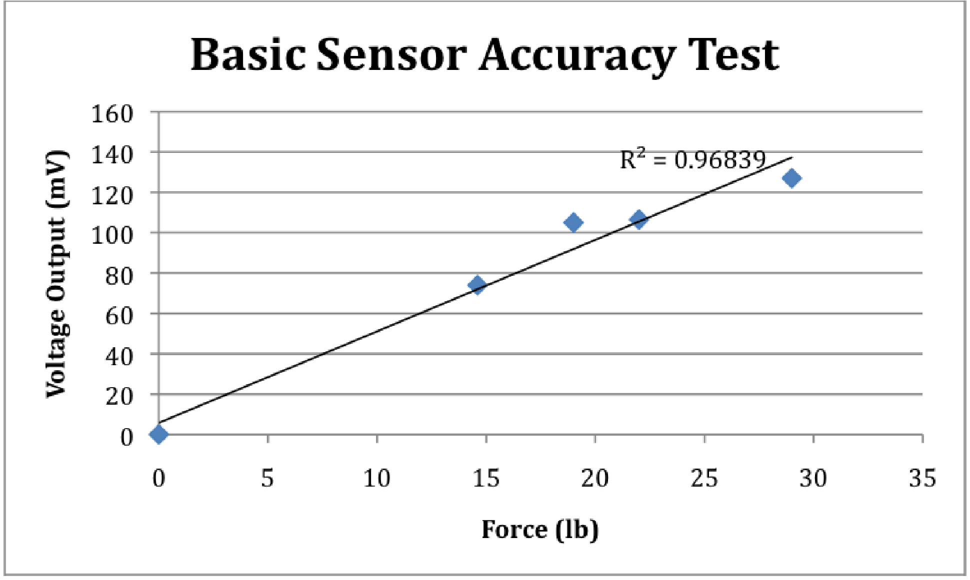

Figure 5 Test of sensor accuracy using voltage output from the sensor and the load resistor.

As shown by the R-squared value in Figure 5, the sensor is accurate within the needed 10% .

5.1.2 Temperature Sensitivity

In order to test the temperature sensitivity, the force was kept constant while an object placed under the sensor heated up. Throughout the test, which went to a temperature slightly higher than body temperature, the output voltage only varied .05%. This shows that the FlexiForce A201 sensors successfully avoids the main problem encountered with the piezoelectric sensor used in earlier models.

5.2 Preliminary Device Tests

The working circuit was tested against a force plate. The force plate, used by CHOP, is known to be very accurate. The device was placed on top of the force plate and stepped on one time. The reading from the force plate is shown in the top of Figure 6 and the reading from the FootPAD device is shown in the bottom of Figure 6.

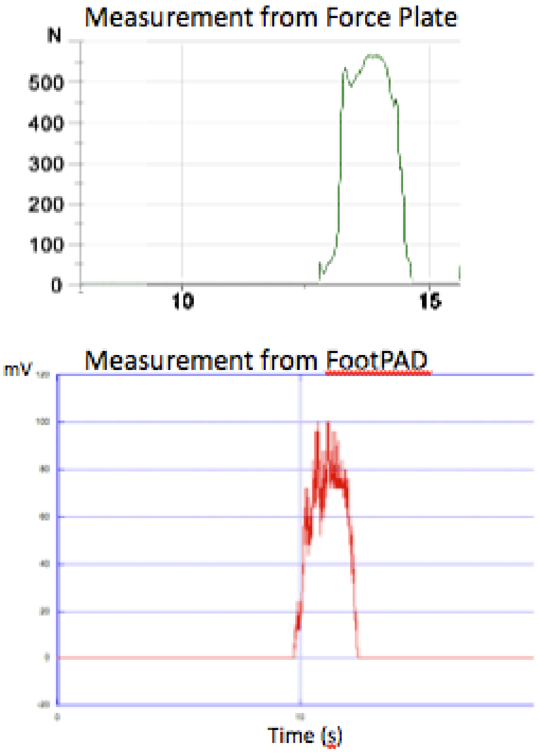

Figure 6 Step test as recorded by the force plate and the FootPAD.

The profile of the two recordings is very similar. This indicates that the device is working correctly and the potential to be calibrated with the force plate. It is important to note that the force plat is recording an average of the forces over the foot, while the FootPAD is recording only the point force acting on one area of the heel. This difference in measuring can account for the difference seen in the recording.

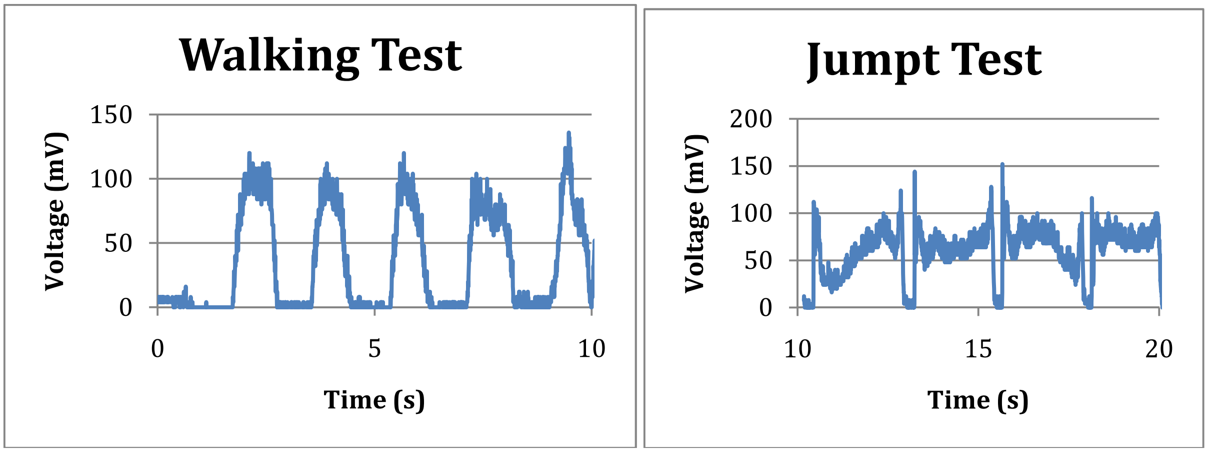

Figure 7 Voltage output data from walking and jump test performed with the FootPAD.

The other tests done with the FootPAD were a walking test and a jumping test. These were both done by having the device attached to the ankle of the tester and the sensor attached to the heel of the shoe. As can be seen in Figure 7, both of these tests gave results with consistent readings. In addition these tests were repeatable and the profiles. This consistency shows that the device will be able to accurately measure the forces applied to the load bearing bones.

6. CONCLUSIONS

Preliminary tests with the sensor on a breadboard demonstrated the viability of using a piezoresistance sensor for the FootPAD device. A circuit, which will be used in the device, was designed and built. A procedure for doing this completely in the lab was also developed. This procedure will make it possible for the device to be consistently reproduced and modifications made easily as needed when Dr. Babette Zemel is using the device. The preliminary tests show promise for the usability of the device as it is designed currently. However, much work is still needed before the device can be fully implemented.

7. FUTURE WORK

7.1 Software

Although the circuit is set up to work with two sensors, one at the ball of the foot and the other at the heel of the foot, the software can currently only read in one sensor. In order to get more accurate data this needs to be modified so that it can read from both sensors during the same trial.

7.2 User Interface

Currently data can be taken off of the device using either the graphical user interface developed for the Neonur or through the hyperterminal. It is important that the device be simple enough for anyone to use. The hyperterminal requires extra knowledge, so it is best if a person does not need to use this. Although the Neonur application is straightforward, it has extra functionality that is not necessary for this device and does not work with data coming in from two channels. It would be best if the user interface were created to only connect to the device, export two text files with the data in from testing, and allow for data collection with a real-time graph of the results.

7.3 Device Testing

Although the device is operational, it was not fully tested due to time constraints. The FootPAD now needs to be tested and calibrated. A past SUNFEST fellow[11] created a device meant to calibrate the FootPAD. This device uses a clock motor to cyclically load the FootPAD, imitating the loading present while walking. It is important to calibrate the device in order ensure accurate measurements. In addition, testing with the device in a shoe is important. This type of testing will show how the device works with the added heat and friction present in a shoe and the constantly changing loads while a person walks.

7.4 Shoe Integration

A key aspect for the device to be successfully used with children is that it be “invisible.” For this to be true the device needs be integrated in a package that can be put in any sized shoe with padding, so that it cannot be felt. In addition it needs to be able to be easily removed and replaced, so that the parent or researcher can collect the data without the child noticing. If children are aware of the presence of the device they are likely to either play with it or change their habits.

8. ACKNOWLEDGMENTS

I would like to thank my advisor Dr. Jay Zemel. He has truly been a great mentor. He is always willing to help me and make sure I fully understand everything. I really appreciate his focus on learning over results. I would also like to thank Dr. Van der Spiegel. He has done an amazing job organizing the SUNFEST program with workshops and guest speakers throughout the summer. I would also like to thank Sanket Doshi for all of his help with the programming, even as he was moving across the country. In addition, I would like to thank all of the SUNFEST and LSRM fellows for making this summer such a great experience. Lastly, I would like to thank the National Science Foundation for funding this program and making this amazing experience possible.

9. RESOURCES

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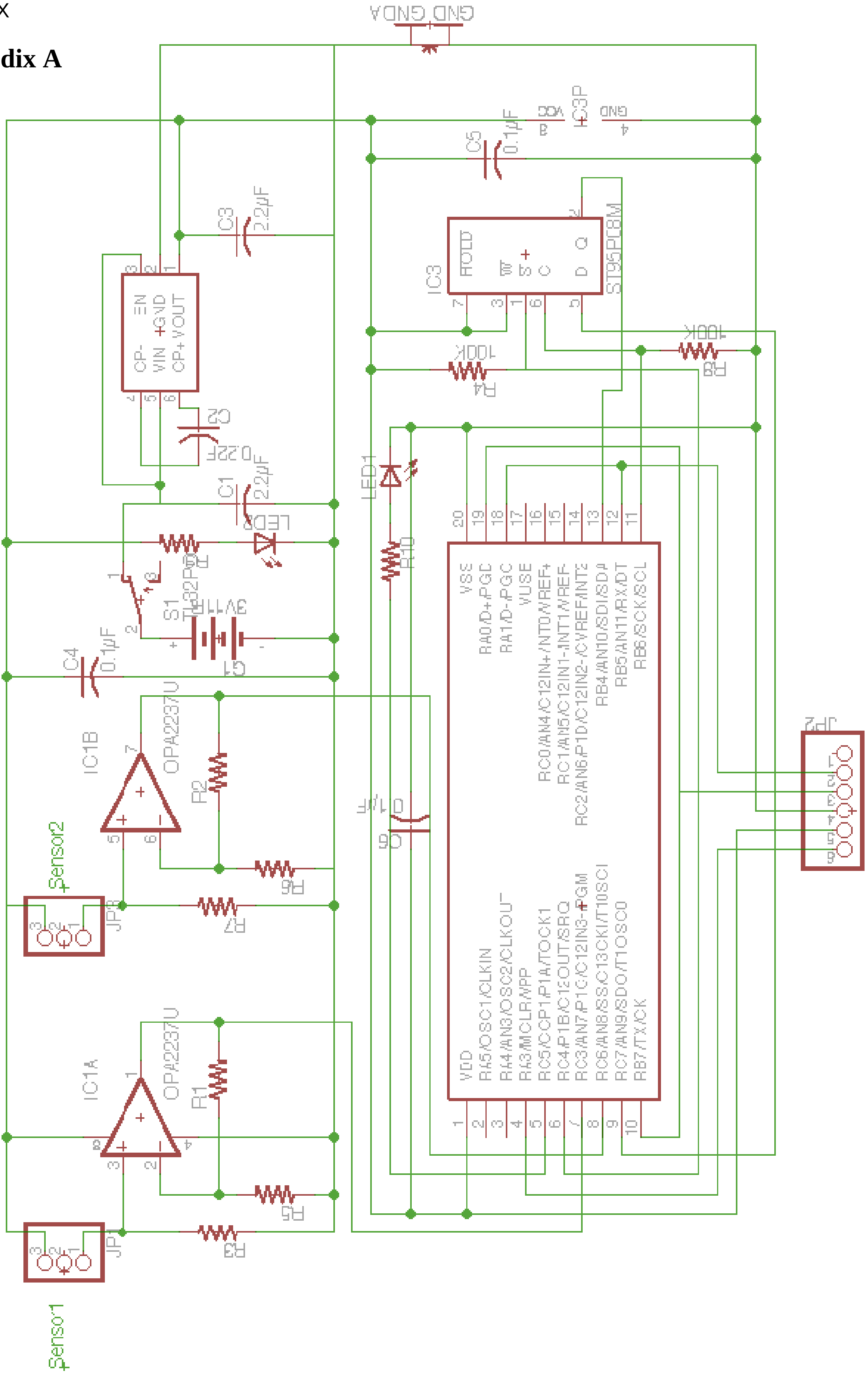
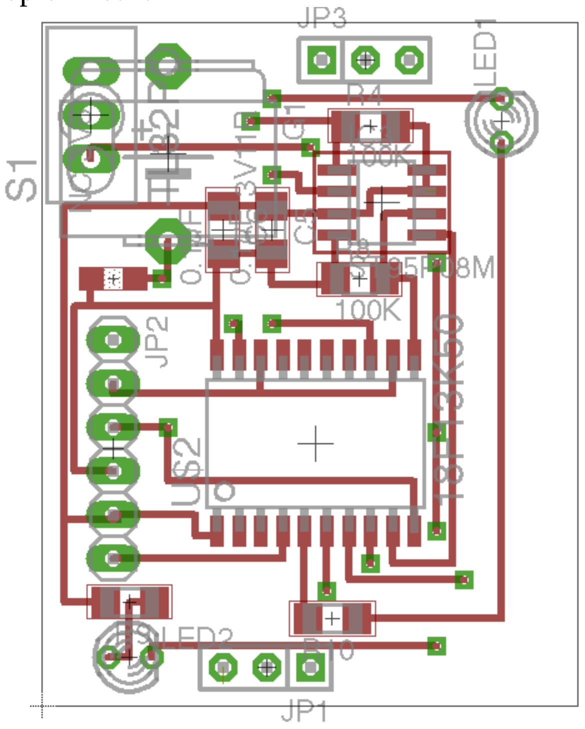
10. APPENDIX

10.1 Appendix A

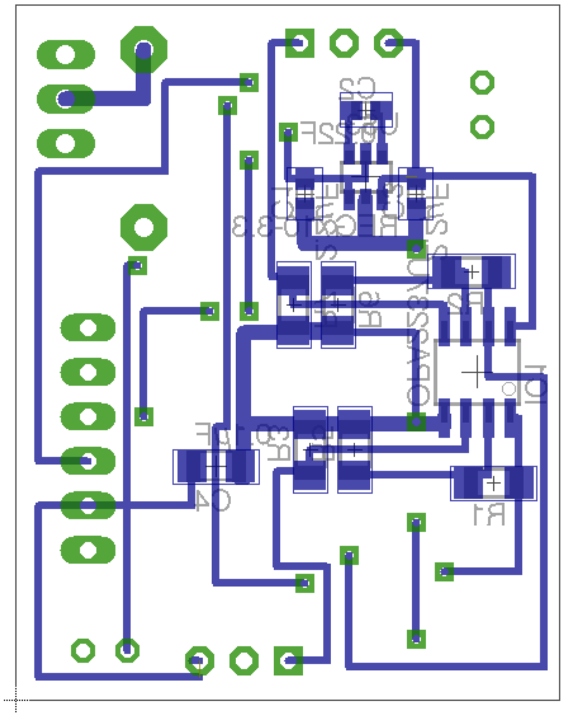


10.2 Appendix B

Top of Board

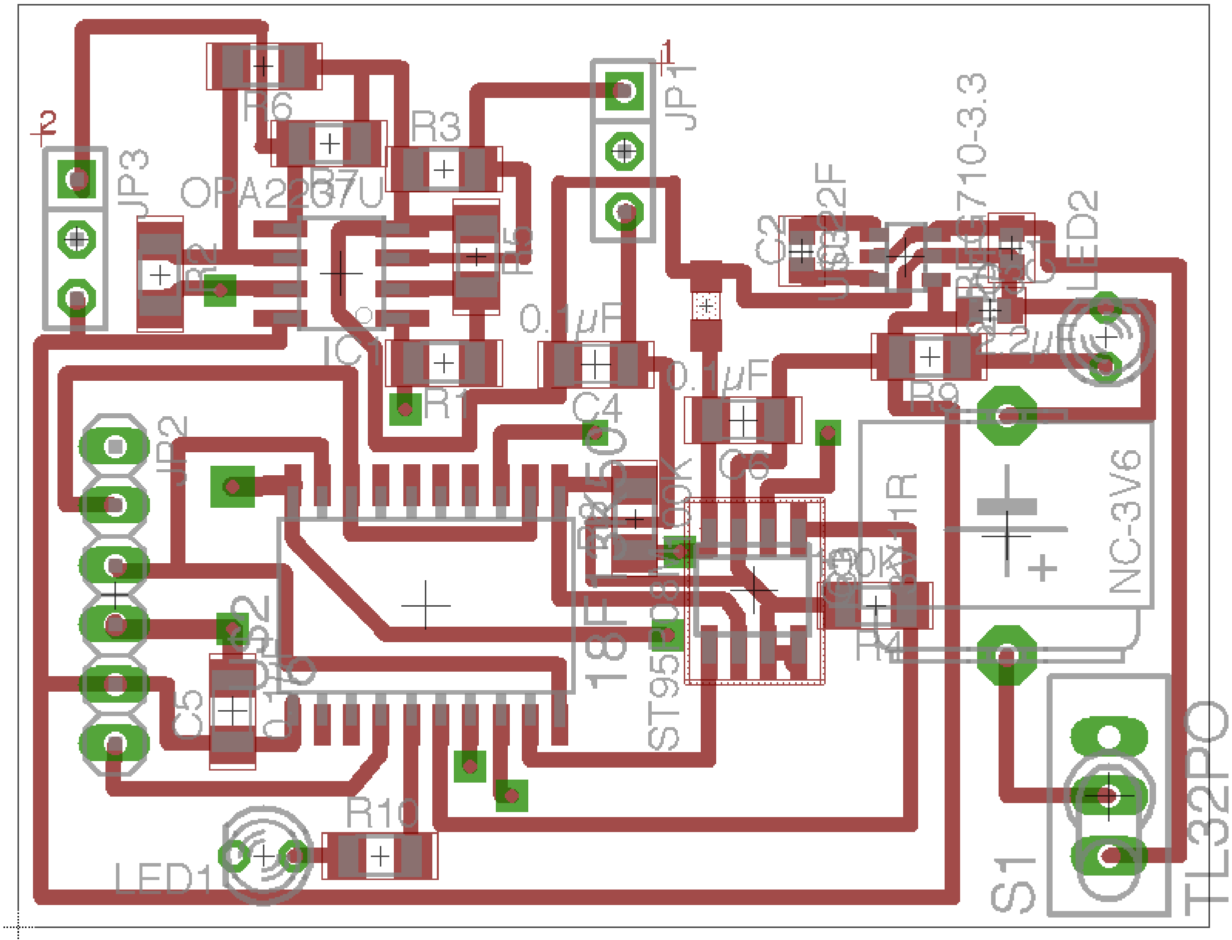


Back of Board



10.3 Appendix C

Top of Board



Bottom of Board