ENGR–UH 4010: Senior Capstone Seminar

Final Report

Automated Fetal Kick-rate Monitoring Belt

Group - 6

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1. Abstract

Monitoring fetal well-being is a crucial procedure in modern obstetrics. Among the many methods of checking fetal well-being, fetal movement detection is widely used to identify changes in fetal activity and reduce the possibility of fetal distress and stillbirth. Standard clinical practice of fetal movement monitoring involves the use of ultrasound which relies on high frequency sound waves to generate an image of the fetus. Doctors also recommend pregnant women to use fetal kick counting as a way to monitor their baby's health beginning from the third trimester. Fetal movement counting is a method by which pregnant women quantify the movements they feel to assess the condition of their baby. Although fetal kick can vary on daily bases, a significant deviation from the normally expected value, which is 10 kicks in 2 hours, indicates that the woman should consult her medical provider. While fetal movement can be observed using ultrasound imaging, a non-invasive and home based monitoring system is still in development to enable pregnant women perform self-administrated monitoring. In this project, an Automated Fetal Kick system will developed by using a matrix of Force Sensitive Resistors(FSRs), and multiplexers. The final product integrates the array of sensors in a maternal belt, and sends information about the fetal movement to a cell phone via wireless communication. The system will be able to detect a fetal force which found to be 0.52 ± 0.15 N, with more than 90% overall efficiency.

2. Problem Definition

a. Problem analysis

1. What does the problem seem to be?

Fetal movement counting is a method used by mothers to quantify their baby's movement. Babies' activity in the womb varies considerably as some might be very active while others are not very active. However, a significant decrease in a baby's normal pattern of movement from the expected threshold indicates that the baby is struggling for reasons such as fetal distress, which is a condition that typically results when the fetus does not receive adequate amount of oxygen. Currently, most mothers keep track of their baby's movement by counting manually or going to the hospital to observe the movement using Ultrasound. Counting baby kicks manually poses a problem as it is subjective and requires hours of concentration.

2. What are the resources?

To help facilitate the counting process, devices that aid the kick counting process have been introduced. Generally, these methods can be classified into two. The first method uses a counter device with a button that needs to be pressed whenever the mother feels a kick. One such device is called KickTrak Baby Kick Monitoring System by Unisar [10]. The second method involves a mobile application which allows the mother to record the kicks whenever she feels a movement. However, both methods are not automatic; hence, they are still subjective and inconvenient to be used.

3. Who has the problem

Physicians advice every pregnant woman to keep track of their baby’s movement starting from their third trimester (28^{th} week). There are three group of pregnant women who are affected by the lack of an automatic and home-based means of counting baby kicks. These are primigravida (first time pregnant women), working women and women who have encountered several complications during earlier pregnancies.

4. Why does the problem occur?

Primigravida are affected as they may not recognize fetus movement properly. Working pregnant woman do not also have the required amount of time to solely concentrate on their baby kicks. On the other hand, women who have encountered complications in their previous pregnancies need to monitor their baby’s well-being in a standardized and reliable manner.

5. When does the problem occur?

Mothers can start feeling their baby’s movement as early as 16-20 weeks. However, baby kick/movement counting is particularly important beginning the third trimester (28^{th} weeks. Hence, the problem occurs whenever a mother starts monitoring her fetus movement pattern.

6. How does the problem occur?

The problem occurs as women spend time (2 or more hours daily) while manually counting and monitoring their baby kicks during the third trimester of their pregnancy.

b. Problem clarification

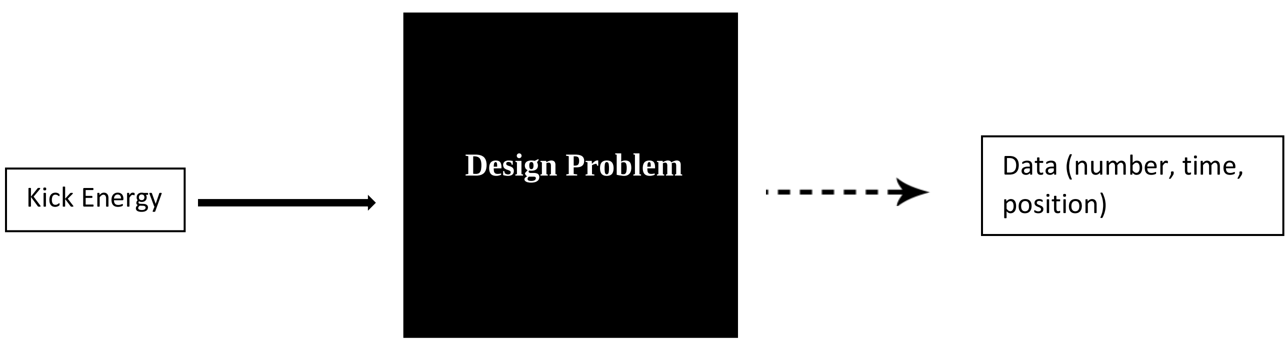


Figure 1: a) Black box model of the Automatic Fetal Kick Counter

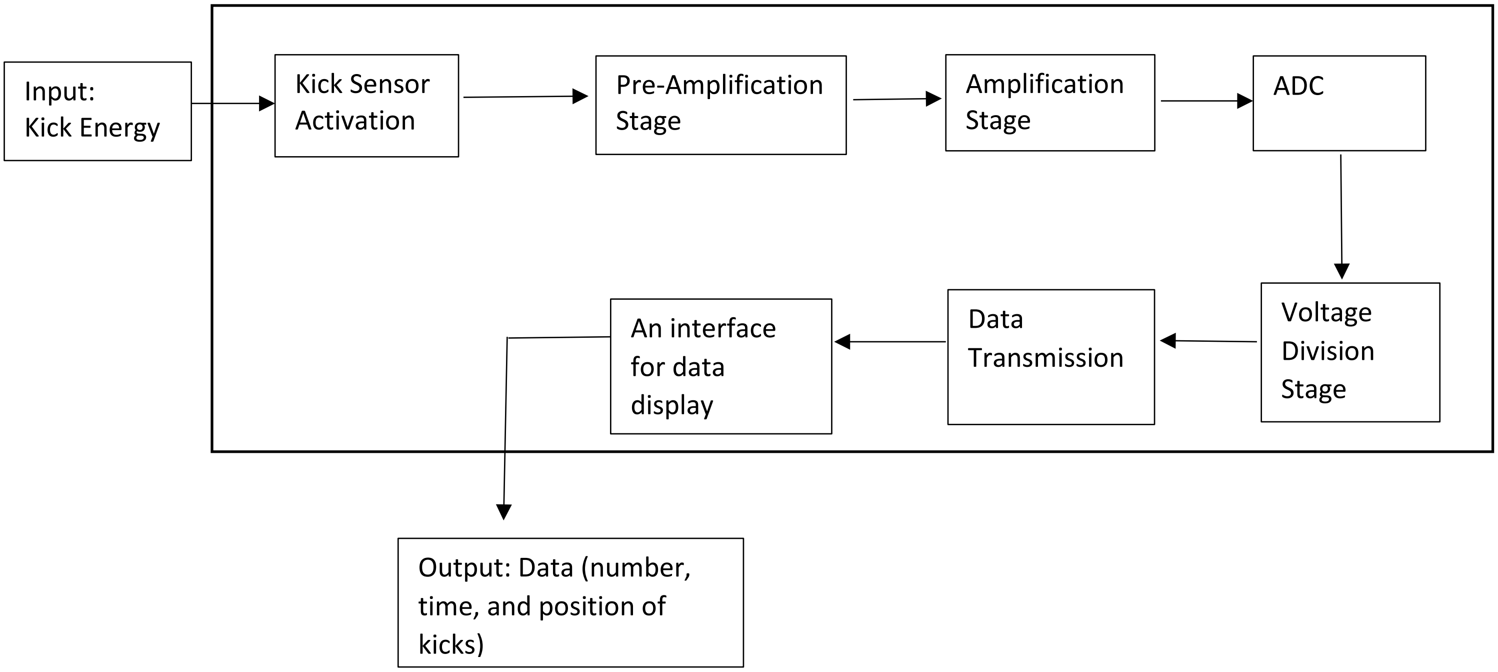


Figure 1: b) Automatic Fetal Kick counter decomposed into sub-problems

Figure 1 (a) shows the initial black-box model of the of the Automatic Fetal Kick Counter system. The system detects the mechanical energy coming from the fetal kick, and gives an output that displays the data, which is the number of kicks in the given time window, and the time at which the kicks occurred. Figure 1(b) illustrates the decomposition of the black-box into sub functions with the corresponding energy and signal flow. As observed in the figure, the kick from the baby activates the kick sensors which will be arranged in a matrix form. The information regarding the kick will be carried in an electrical signal which is in the form of an output voltage. The signal will then pass through a pre-amplification stage which is necessary to prepare the signal to be amplified in the required range of operation. Consequently, the signal will be amplified, and converted to digital data. The digital data will then be processed, and transmitted to an output interface such as a personal computer or cell phone.

c. Problem Statement

In this capstone project, our task is to design a non-invasive, automatic fetal kick counting system made up of a force sensor matrix that will be integrated into maternity support belts to allow home based fetal health monitoring with an efficiency of more than 90%.

d. Design Constraints

The design constraints are divided into technical and non-technical constraints.

i) Technical Constraints

The primary technical constraint is the sensitivity of the FSR that will be used in the design. The force sensor matrix array should be able to detect forces as low as 0.52 ± 0.15 N, which is the typical range for fetal kicks, and display the output on a suitable scale to observe and monitor the kick signals.

The second constraint involves power and current constraints. The possibility of powering the fetal kick-monitoring system from the mobile phone was considered. However, providing an external power supply is more suitable due to the power consumption. A typical coin cell supplies 630 mAh, while 5.45 mAh is the maximum battery capacity from a mobile phone. For wearable technologies, the E-textile battery (model R5480) is commonly used due to its low current delivery to power electronics sewn in fabric. A maximum total current of 100 uA was also set as constraint for safety reasons.

The following characteristics of R5480 E-Textiles Battery are the constraints for the power consumption.

- Operating voltage of 1.5-5.0 V
- Power Dissipation of 150 mW
- Supply current : 4.0 mAh

The data transmission of the wireless Bluetooth module that will be connected to the system depends on the baud rate. To calculate the data transmission rate for the sensor belt prototype, we can do the following calculations:

$$Data\ rate = \#\ of\ sensors\ x\ ADC\ resolution\ x\ Sampling\ rate$$

The data transmitted from the sensor must be compatible with the transmission limit of the Bluetooth wireless module used. For our system a baud rate of 9600 bps was chosen.

Finally, the total cost of the system is aimed to be under $500 due to the high cost of the individual force sensors. The cost will be reduced when the product is mass produced.

ii) Non-technical

The non-technical details include maintaining the privacy and security of the mother while recording the fetal kick measurements. The Institutional Review Board (IRB) is a committee that applies research ethics by reviewing the methods proposed for research to ensure they are ethical and do not harm the subjects involved in the experimental process. We will also have obtained the IRB approval by the time we take input from the pregnant women on the design of our kick-monitoring belt.

e. Criteria for design evaluation and testing

The following criteria were considered for the design evaluation criteria:

a) *Reliable/Efficiency*
   The prototype must be reliable and reproducible. The purpose of the automated kick-monitoring is to a) be sensitive enough to record forces as low as 0.5N and b) effectively amplify it to the desired output voltage range
b) *User Friendly*
   The complete system has to be easy to operate, and should use automatic or hands-free monitoring. Additionally, the sensor environment (the material on which the design will be implemented) must be comfortable to the users.
c) *Durability*
   The proposed design should consume low power, that is, it should be able to transmit data from the belt to the mobile phone for at least two hours continuously.
d) *Portability*
   The final design must be a belt that is portable so that users can easily monitor the fetal movements.
e) *Light weight and small size*
   The design should be lightweight, and of a small size to be easily integrated with the currently used back-support belt.

f. Deliverables Statement

The final product will be a matrix of Force Sensitive Resistors that will be integrated to an existing back-support belt. The design will be an 8 × 8 Force Sensitive Resistor matrix array, with a Bluetooth enabled feature to wirelessly transmit the data from belt to mobile device or computer. It can be used to wirelessly transmit information of baby's kick count and real-time position tracking.
In addition to the belt, we will be developing the user experience (UX) and graphical user interface (GUI) for a mobile application which can be used by the mother to monitor the kicks in real-time.

3. Conceptualization

a. Background Research

Fetal movement is an important measure of the unborn fetus' well-being as it allows physicians to make the necessary intervention when there is fetal compromise and distress. Regular pauses of movement are normal as babies sleep in the womb. However, if babies become less active by showing less movement than what is mostly expected in a given time window, or totally cease to move, it is an indication that the baby is unhealthy. A reduction of fetal movement is linked with fetal hypoxia, which is an increased incidence of stillbirth and fetal growth restriction (FGR). Hence, monitoring fetal movement has been proposed as screening tool for fetal compromise and FGR. Although there are several methods of measuring baby kicks, the American College of Obstetricians and Gynecologists (ACOG) recommends measuring the time it takes to record 10 distinct movements. Perception of 10 kicks within a period of 2 hours is an average value based on the research made on several low-risk pregnant women. Counting baby kicks is effective if it's done daily at the same time after the third trimester of pregnancy (28^{th} week). It should also be done after a meal as it makes the baby active. Although, baby kicks differ from day to day, a significant deviation from the average value suggests a concern regarding the fetus's condition. Al-Ashwal and Rania Hussien state in their research paper "Fetal Kicking Monitoring Device for Intrauterine Death Prevention" that getting to know the typical pattern of the fetal movements is also equally important as keeping track of the number of kicks [2].

Fetal kick counting is monitored through various methods. The methods can generally be classified into two; active and self-reported. Active methods depend on the use of high frequency sound waves to form an image of the fetus. Current medical instruments used in hospitals involve the use of a two-dimensional Doppler ultrasound machine [14]. However, the method can only be used for a limited time, and it is mostly done in hospital environments as it involves prohibitive cost equipment. The safety of the fetus under prolonged exposure of ultrasound is also another concern that is still being studied. Fetal movement can also be reported by the mother and compared to a kick-chart. Although self-reporting can be used for detecting fetal health problems, it is inconvenient as it requires pregnant women to sit down and spend about 2 hours daily focusing on counting the movement starting from the beginning of their third trimester. The method is particularly troublesome for working pregnant women as they will not have suitable time and space to do the measurement. Furthermore, it is exposed to errors due to its subjective nature. It is also difficult for first time pregnant women as they may not be able to recognize fetal movement. Hence, many researches are being conducted to provide a convenient method that use on body sensors to monitor fetal movement.

One method used in researches is concerned with real-time monitoring and remote access using a sealed air bag placed around the mother's abdomen for detecting the intrauterine force exerted on the abdomen by the fetus. This method doesn't use mechanical or electrical power. In the mechanism, the pressure sensor (pressurized bag) sends signal to a microcontroller for conducting signal processing. Consequently, the data will be uploaded to internet cloud services for real time monitoring and remote access [14]. Although the mechanism was beneficial as it was passive, the efficiency was low as it couldn't effectively detect forces less than 1N.

A different method used in research make use of body-worn accelerometers during pregnancy. Accelerometers are sensors that measure the acceleration felt by people and objects due to the gravity force g. The principle behind these sensors is the displacement of small mass etched into the silicon surface of the integrated circuit. As acceleration is applied to the device, a force develops which results in a displacement on the mass. One research study showed that one can obtain optimal results for fetal kick counts by positioning two accelerometers plus a reference accelerometer, which is necessary to discriminate maternal movement, to the back of the patient [3]. The experimental setup was carried out by placing the accelerometers on the abdomen of the pregnant women and comparing the accelerometer data with inputs from two external references: visual analysis by an experienced midwife using ultrasound, and input from the subject through a handheld toggle. The following figure shows the setup used for measuring fetal movement using bodily worn accelerometers.

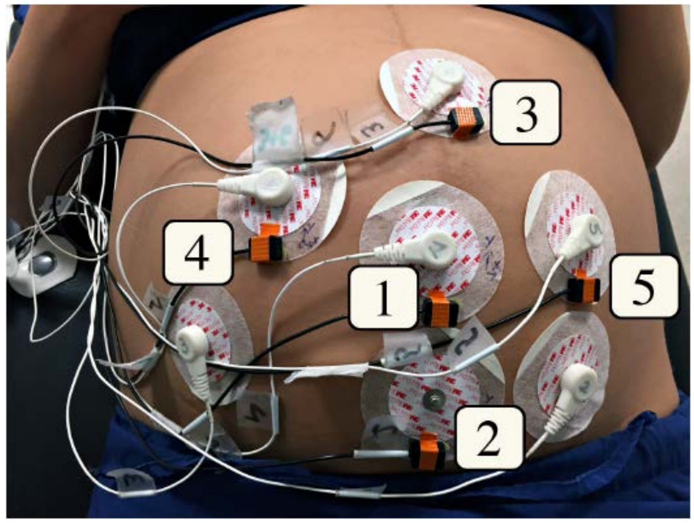


Figure 2: On body accelerometer placement for fetal movement detection

Another ongoing research deals with developing a flexible and stretchable fabric based tactile sensor by placing a sheet of sensitive conductive rubber together with a piezo-resistive fabric on either side of a mesh layer as illustrated in the figure below.

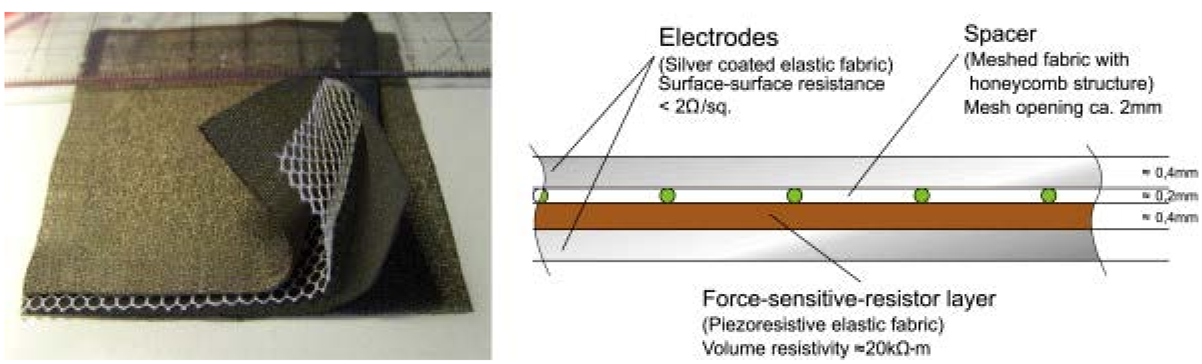


Figure 3: a) photograph of the assembly of the flexible tactile sensor with 4 fabric layers, and b) a schematic representation (Buscher et al.)

Their experiment had high signal repeatability and the finished product had a pressure range of 0–50 kPa (or 5 N/cm^2) which is more than adequate for FM monitoring applications. An advantage of this model is that it is easily molds to natural shapes such as a pregnant woman's abdomen. However, researchers also noted that there was a degradation of performance due to moisture from sweat.

In a research published by Indian Journal of Science and Technology, a matrix of Force Sensitive Resistor was used to detect fetal movement. In paper the authors described that a total of 9 FSRs were used in a 3 by 3 matrix force, and placed on a belt prototype. An Arduino Mega was used as the microcontroller, and an LCD was used to display the output. By setting the threshold for detecting kicks as 0.7N, the prototype was tested, and a 90% efficiency was obtained. The apparatus used for the research is shown below.

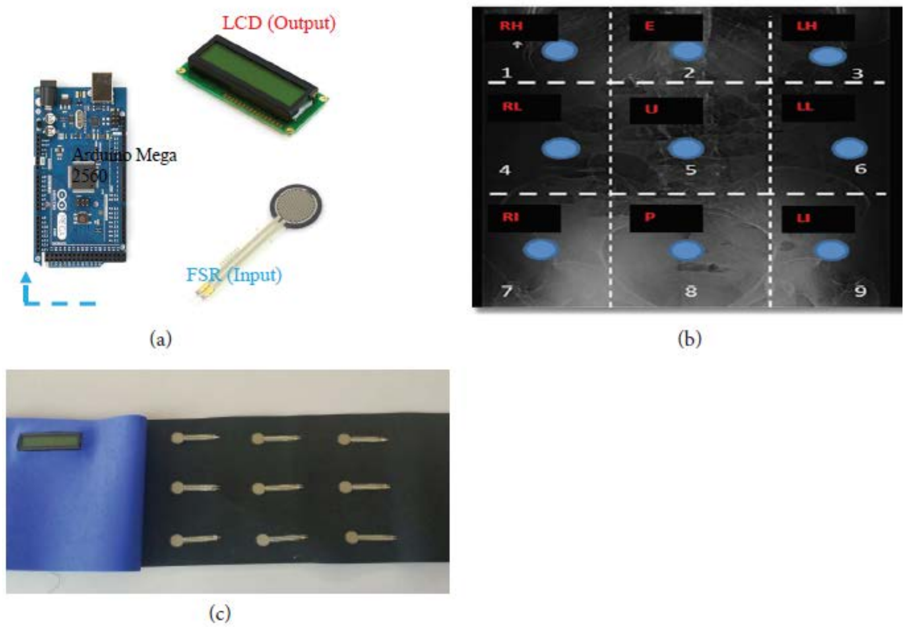


Figure 4: a) Equipment used for system (b) Sensor placement on the abdominal regions (c) belt based prototype

b. Concept generation with morphological charts

The table below shows multiple concept generation using morphological charts. The multiple concepts were generated for the different sub problems listed in the black-box model. These include input sensors, pre-amplification circuit design, amplification circuit design, analog to digital conversion stage, data transmission stage, and an output interface system. Multiple options were considered under each category based on current researches, and circuit design books.

Table 1: Morphological chart for Automatic Fetal Kick Counter

Input Sensors	Pre-amplification Design	Amplification Circuit Design	Analog to Digital Conversion (ADC)	Data Transmission	Output Interface
Force Sensitive Resistors (FSRs)	Wheatstone bridge	Inverting	PCB design	Wireless	PC, desktop computers
Accelerometers	Voltage divider biasing	Differential	Arduino/ Lily-pad	Wired	Cell phones
		Instrumentation	[1]*DAQ		

From the chart it can be shown that 2×2×3×1×2×2 = 48 multiple solutions are generated.

c. Concept selection with Pugh Chart

An important stage of the automatic fetal kick counting system involves the input sensors. The chosen input sensor must be sensitive enough to detect fetal kicks. Furthermore, sensors that are cost efficient, and light are given priority. Hence, cost, weight and sensitivity were chosen to compare the input sensors.

Table 2: Use of AHP pairwise comparison matrix to generate weights for the criteria

	Sensitivity	Weight	Cost	Total	Relative Order
Sensitivity	1.00	3.00	3.00	7.00	0.54
Weight	0.33	1.00	3.00	4.33	0.33
Cost	0.33	0.33	1.00	1.66	0.13

[1]*represents multiple solution for the prototype stage of the project

Table 3: Weighted Pugh chart for the Input sensors of the Automatic Fetal Kick counting system

Concept	Sensitivity	Weight	Cost	Sum	Rank
Relative Order	0.54	0.33	0.13		
Accelerometer	-1	1	-1	-0.34	2
FSRs	B	A	S	E	1

Based on the above comparison, FSRs were chosen to be better inputs for the system.

For the amplification stage, three criteria were compared. These were cost, power and gain. The weights assigned for each criterion is shown in the table below.

Table 4: Use of AHP pairwise comparison matrix to generate weights for the criteria

	Power	Gain	Cost	Total	Relative Order
Gain	1.00	3.00	3.00	7.00	0.54
Power	0.33	1.00	3.00	4.33	0.33
Cost	0.33	0.33	1.00	1.66	0.13

Table 5: Weighted Pugh chart for the amplification circuit of the Automatic Fetal Kick counting system (concept 3 baseline)

Concept	Power	Gain	Cost	Sum	Rank
Relative Order	0.54	0.33	0.13		
Inverting	1	-1	1	0.08	1
Differential	1	-1	1	0.08	1
Instrumentation	B	A	S	E	2

Table 6: Weighted Pugh chart for the amplification circuit of the Automatic Fetal Kick counting system (concept 2 baseline)

Concept	Power	Gain	Cost	Sum	Rank
Relative Order	0.54	0.33	0.13		
Inverting	1	-1	1	0.34	1
Differential	B	A	S	E	2
Instrumentation	-1	1	-1	-0.34	3

Table 7: Weighted Pugh chart for the amplification circuit of the Automatic Fetal Kick counting system (concept 1 baseline)

Concept	Power	Gain	Cost	Sum	Rank
Relative Order	0.54	0.33	0.13		
Inverting	B	A	S	E	2
Differential	-1	1	-1	-0.34	1
Instrumentation	-1	1	-1	-0.34	1

Based on the above comparison, instrumentation amplifier was found to be better when gain is given more importance. On the other hand, inverting amplifier was found to be better in terms of cost and power consumption.

Table 8: Use of AHP pairwise comparison matrix to generate weights for the criteria

	User friendliness	Power	Cost	Total	Relative Order
User friendliness	1.00	3.00	3.00	7.00	0.54
Power	0.33	1.00	3.00	4.33	0.33
Cost	0.33	0.33	1.00	1.66	0.13

Table 9: Weighted Pugh chart for the amplification circuit of the Automatic Fetal Kick counting system (concept 2 baseline)

Concept	User Friendliness	Power	Cost	Sum	Rank
Relative Order	0.54	0.33	0.13		
Wireless	1	-1	-1	0.08	1
Wired	B	A	S	E	2

Although, there is some advantage to wired transmission due to its relatively lower power consumption and low cost, wireless transmission allows the final product to be more user friendly, and convenient system. Hence, it was decided to wireless transmission to send the data from the fetal movement monitoring system to a mobile device.

4. Project management tools

Below are the different project management tools that we used in our project. We used the following techniques:

a) Work breakdown structure (WBS) was used to decompose our project into smaller tasks and subtasks, with estimates for task start and end dates.

b) The Gantt chart, or milestone chart, is another widely used method and enables us to see the list of tasks to be performed across the time frame on the horizontal axis.

a) Design structure matrix (DSM)

a. Work breakdown structure

Table 10: Work breakdown structure of our project

FETAL KICK MONITORING BELT			
Tasks	**Subtasks**	**Dates and duration**	
		Start Date	End Date
1.0 literature review	1.1 Search for literature on sleep apnea	Sep-5	Sep-17
	1.2 Current diagnosis of sleep apnea	Sep-17	Sep-23
	1.3 Brainstorm possible design solutions	Sep-23	Sep-28
	1.4 Consult with experts	Oct-2	Oct-12
2.0 mini project: heart rate	2.1 Obtain skills for capstone project	Sep-16	Oct-20
	2.2 Familiarizing with literature	Oct-15	Oct-24
	2.3 Assemble components for the mini-project	Sept-20	Oct-3
	2.4 Id limitations of our project	Jan-5	Jan-10
		Jan-10	Jan-13
3.0 revision of problem statement	3.1 Customer need from literature review	Jan-13	Jan-20
	3.2 Id better area of application based on further research	Oct-15	Oct-23
	3.3 Research new literature	Oct-20	Oct-27
4.0 Generate concepts	4.1 Research multiple solutions (i.e. Morphological charts)	Nov-2	Nov-12
	4.2 Black-box modelling	Nov-3	Nov-8
	4.3 Problem analysis (questions	Nov-8	Nov-16
5.0 detail design	5.1 Selection of solution	Nov-21	Nov-26
	5.2 Modelling and simulation	Jan-2	Jan-5

	5.3 Id required components	Jan-6	Jan-13
	5.4 Finalize design	Jan-10	Jan-13
WINTER BREAK			
6.0 IRB approval	Outline project goals, explaining how information will be used	Jan-5	Jan-10
	6.2 Fill forms	Jan-10	Jan-13
	6.3 Develop preliminary testing methods	Jan-2	Jan-12
7.0 Build prototype	7.1 Id stages in design	Jan-24	Feb-15
	7.2 Iterative design	Feb-2	Feb-17
	7.3 Assemble prototype	Mar-1	Mar-8
	7.4 Test components	Mar-18	Mar-30
8.0 Test prototype	8.1 Further develop testing methods	Apr-1	Apr-14
	8.2 Perform tests/IRB approval	NA	NA
8.0 document and reporting	9.1 Fall 1: Progress report 1 prep	Sep-13	Sep-17
	9.2 Fall 1: Progress report 2 prep	Oct-13	Oct-16
	9.3 Mini-project presentation prep	Oct-18	Oct-22
	9.4 Fall 2: Progress report 1 prep	Nov-22	Nov-26
	9.5 Fall 2: Progress report 2 prep	Nov-28	Dec-3
	9.6 Capstone proposal presentation	Dec-6	Dec-10
	9.7 Spring 1: Progress report prep	Feb-11	Feb-15
	9.8 Spring 2: Intermediate report prep	Mar-8	Mar-12
	9.9 Writing final report	Apr-10	May-5

b. Design Structure matrix (DSM)

Below is the design matrix for our project

Tasks																											
		DESIGN STRUCTURE MATRIX																									
	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4	3.1	3.2	3.3	4.1	4.2	4.3	5.1	5.2	5.3	6.1	6.2	6.3	7.1	7.2	7.3	7.4	8.1	8.2	8.3
1.1 Search for literature on sleep apnea	1.1																										
1.2 Current diagnosis of sleep apnea		1.2																									
1.3 Brainstorm possible design solutions		x	1.3																								
1.4 Consult with experts		x	x	1.4																							
2.1 Obtain skills for capstone project				x	2.1																						
2.2 Familiarising with literature						2.2																					
2.3 Assemble components for the mini-project						x	2.3																				
2.4 Id limitations of our project						x	x	2.4																			
3.1 Customer need from literature review				x				x	3.1	x																	
3.2 Id better area of application based on further research									x	3.2	x																
3.3 Research new literature										x	3.3																
4.1 Research multiple solutions for proj (i.e.morphological charts											x	4.1															
4.2 Black-box modelling											x		4.2														
4.3 Problem analysis (questions													x	4.3													
5.1 Selection of solution														x	5.1												
5.2 Modelling and simulation														x	x	5.2											
5.3 Id required components																x	5.3										
6.1 Outline project goals, explaining how information will be used														x				6.1									
6.2 Fill forms																		x	6.2								
6.3 Develop prelim testing methods														x				x	x	6.3							
7.1 Id stages in design																				x	7.1						
7.2 Iterative design																					x	7.2	x				
7.3 Assemble prototype																							7.3				
7.4 Test components once IRB approval obtained																							x	7.4			
8.1 Further develop testing methods																								x	8.1		
8.2 Design a mobile app																										8.2	
8.3 Perform tests																							x				8.3
9.1 Final report preparation																										x	x

Fig. 5: Design structure matrix, with interdependencies shown between the subtasks

c. Critical Path Method (CPM)

The critical path method is shown in Table 11 below. The critical path is determined through noting the backward pass calculations, and is shown in Table below by the red arrows.

Table 11: Critical path method outline

				30 5 35				55 20 75		75 14 89		89 14 103		
				Design solution				Build prototype		PCB design	→	Test product		
				35 0 35				55 0 75		75 0 89		89 0 103		
0 20 20		20 10 30	↗		↘	35 20 55	↗		↘ ↗				↘	103 13 116
Literature review	→	Concept generation				IRB approval								Final documentation
4 0 24		24 10 34	↘			35 20 55								103 0 116
				30 4 34	↗		↘	55 14 69	↗ ↘		75 25 100		↗	
				Simulation				Iterative design			Mobile app design			
				34 1 35				69 6 75			78 25 103			

d. Gantt chart

Below is the Gantt chart that tracks our weekly progress in order to complete this project in the given time period.

Start	End	Tasks
Sep-4	May-5	Tasks
Sep-5	Sep-17	1.1 Search for literature on sleep apnea
Sep-17	Sep-23	1.2 Current diagnosis of sleep apnea
Sep-23	Sep-28	1.3 Brainstorm possible design solutions
Oct-2	Oct-12	1.4 Consult with experts
Sep-16	Oct-20	2.1 Obtain skills for capstone project
Sep-15	Sep-24	2.2 Familiarising with literature
Sep-20	Oct-3	2.3 Assemble components for the mini-project
Sep-25	Oct-14	2.4 Work on mini-project
Oct-5	Oct-17	2.5 Id limitations of our project
Oct-17	Oct-23	3.1 Customer need from literature review
Oct-15	Oct-23	3.2 Id better application based on further research
Oct-20	Oct-27	3.3 Research literature for fetal kick-monitoring
Nov-2	Nov-12	4.1 Research multiple solutions
Nov-3	Nov-8	4.2 Black-box modelling
Nov-8	Nov-16	4.3 Problem analysis (questions
Nov-21	Nov-26	5.1 Selection of solution
		WINTER BREAK
Jan-2	Jan-5	5.2 Modelling and simulation
Jan-5	Jan-10	5.3 Id required components
Jan-10	Jan-13	5.4 Finalise design
Jan-14	Jan-16	6.1 Outline project goals
Feb-1	Feb-13	6.2 Fill forms for IRB approval
Jan-23	Feb-14	6.3 Develop preliminary testing methods
Jan-24	2/15/2018	7.1 Id stages in design
Feb-2	Feb-17	7.2 Iterative design
Mar-1	Mar-8	7.3 Assemble prototype
Mar-18	Mar-30	7.4 Test components
Apr-1	Apr-14	8.1 Further develop testing methods
Apr-15	Apr-26	8.2 Perform tests

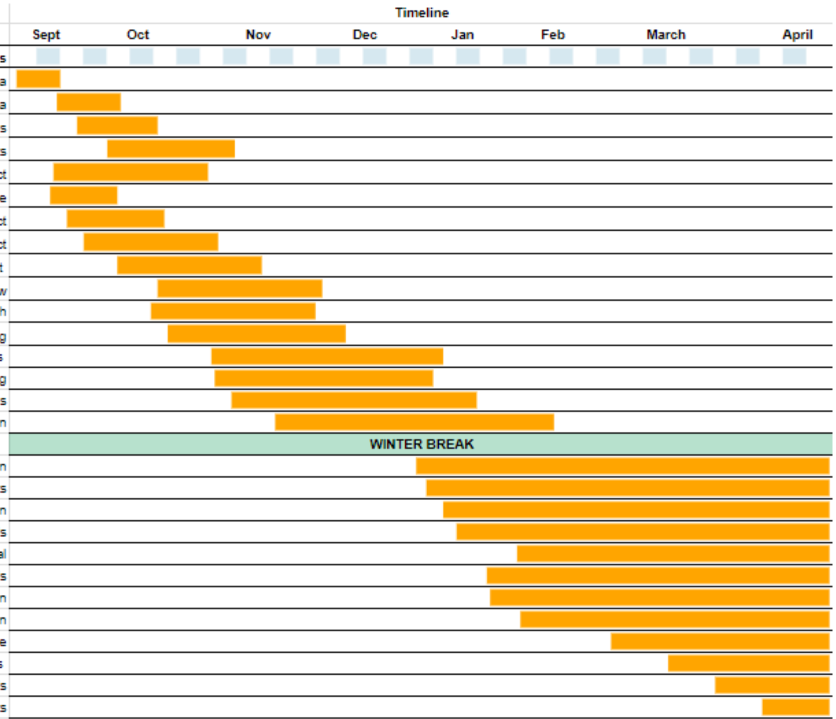


Fig. 6: Gantt chart with task deadlines

5. Modeling, Simulation and Optimization Plan

a. Modeling

The Automated Fetal Kick monitoring system will consist of an 8 x 8 Force Sensitive Resistors matrix. A demultiplexer and a multiplexer are used to supply power to the sensor matrix column and to scan through the rows of the matrix to detect a change of resistance value. The system is designed in such a way that a fetal kick activates one FSR at a time. However, since every sensor in the matrix is scanned at high frequency, it is possible to capture the presence of kicks at multiple positions.

The force vs resistance graph of the Force Sensitive Resistance (FSR) was used to determine the magnitude of the resistance value that corresponds to the range of kick force which is 0.52 ± 0.15 N. The range of resistance value was computed for two standard deviations under the occurrence of fetal kick.

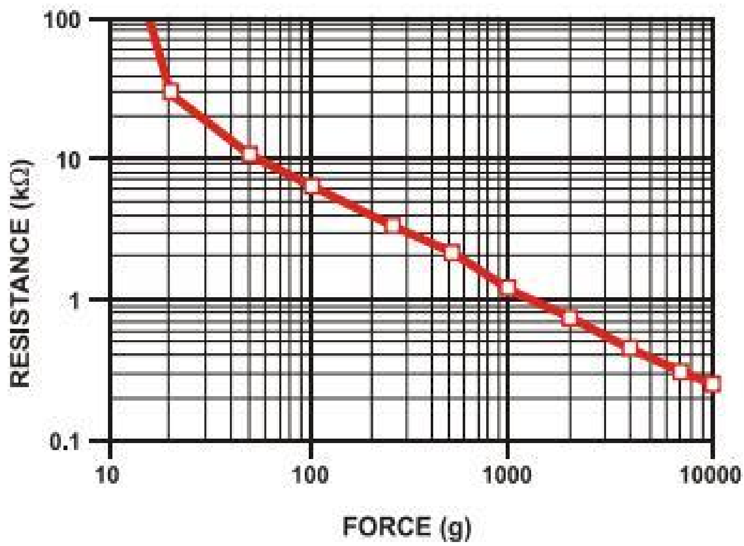


Figure 7: Force vs Resistance graph for a Force Sensitive Resistor

Considering two standard deviations from the average fetal kick, the minimum force from fetal kick is obtained to be 0.22N (22.4g) and the maximum force was obtained to be 0. 82N (83.6g). These values are mapped to resistance values of 6KΩ and 30 KΩ respectively.

I. Pre-Amplification and Amplification Stage

The amplifier stage is modeled using a biased amplifier that has the configuration shown below

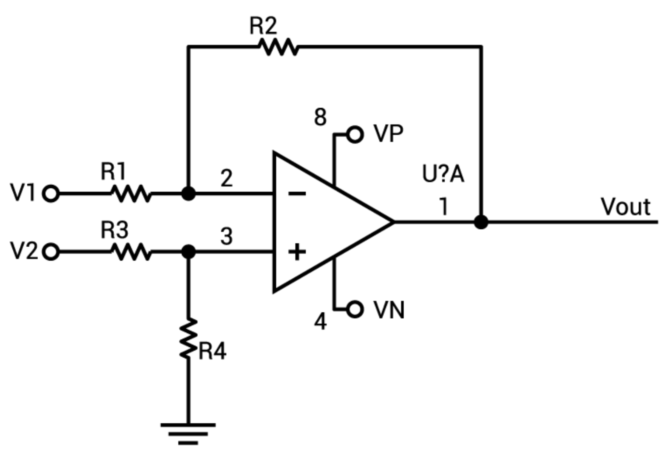


Figure 8: Biased inverting amplifier

In the above figure the resistor labeled as R1 represents the FSR which is a variable resistor. To obtain appropriate values for resistors R2, R3 and R4 that are shown in figure 8, the sensitivity $\left(\frac{\partial V}{\partial R}\right)$ and the magnitude of the output voltage were analyzed using the appropriate range of the variable resistance (R1) value which is in between 6KΩ and 30 KΩ as determined from the possible kick ranges by referring to the FSR datasheet.

In the model, we considered the following three parameters R1, R2, and R1_min. R1 is the resistance from the FSR and R2 is the feedback resistance as shown in Figure 8. R1_min is defined as the minimum resistance of the FSR which corresponds with the highest measurable force from fetal kick.

Using the equations of inverting amplifier the sensitivity and the output voltage equations were obtained to be the following;

The plots of sensitivity versus the FSRs resistance (R1), and output voltage versus R1 for R1_min= 6kΩ corresponding with a force of 0. 82N are illustrated in Figures 9 and 10 respectively.

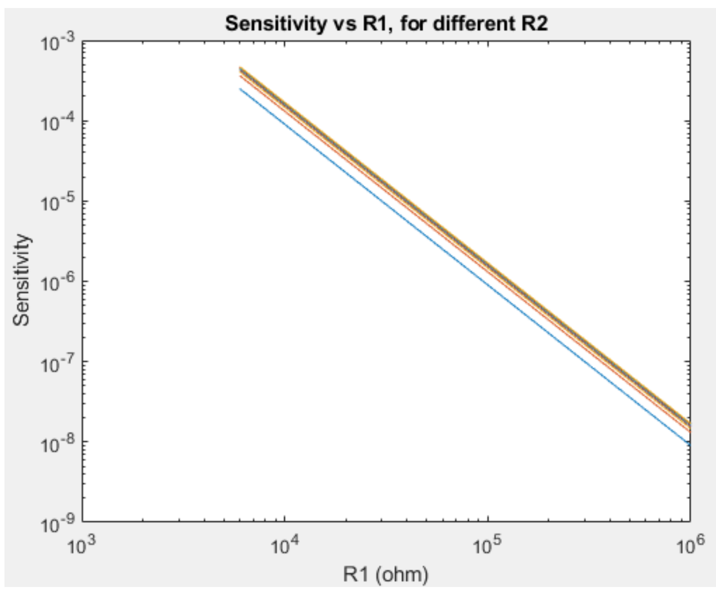


Figure 9: Plot of Sensitivity versus R1

From figure 9 we observe that as the feedback resistance (R2) increases, the sensitivity graphs increase monotonically. The resistance for R1 is modeled from 6kΩ to 1MΩ, and the graphs correspond with resistance values of R2 from 6kΩ (which corresponds with the blue line) to 100 kΩ.

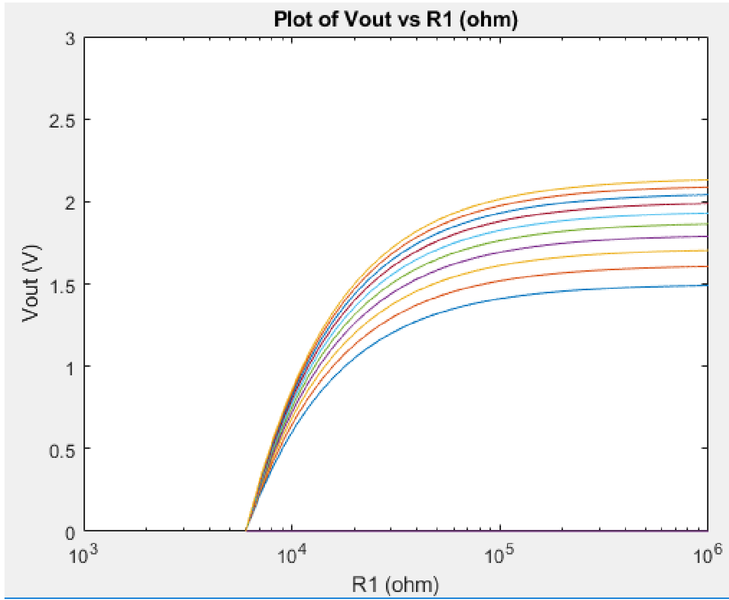


Figure 10: Plot of output voltage versus R1

The above figure shows the output voltage for different R2 values, keeping R_min at 6kΩ. We note that as R2 increases from 6kΩ to 1MΩ, there is a higher voltage output. Since we are interested in the output voltage at resistances around 10kΩ, we decided a suitable value of R2 as 30kΩ. The chosen resistance value gives an output voltage ranging from 0.5-2.5 V around our region of interest as shown in Figure 11 below.

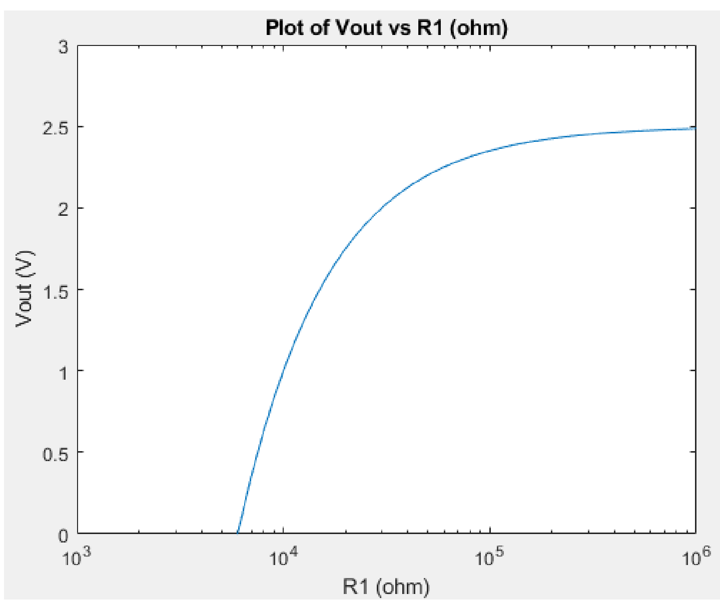


Figure 11: Plot of Vout vs R1, for R2 at 30kΩ

Finally, in order to observe the effect of changing R1_min, we plotted a graph of the output voltage vs R1. Below is the graph that we obtained for R1_min values ranging from 6kΩ to 10kΩ. Since only the positive values of voltage as considered, we can clearly observe from the plots that the higher resistances of R1_min, the lower the range of the measurable forces.

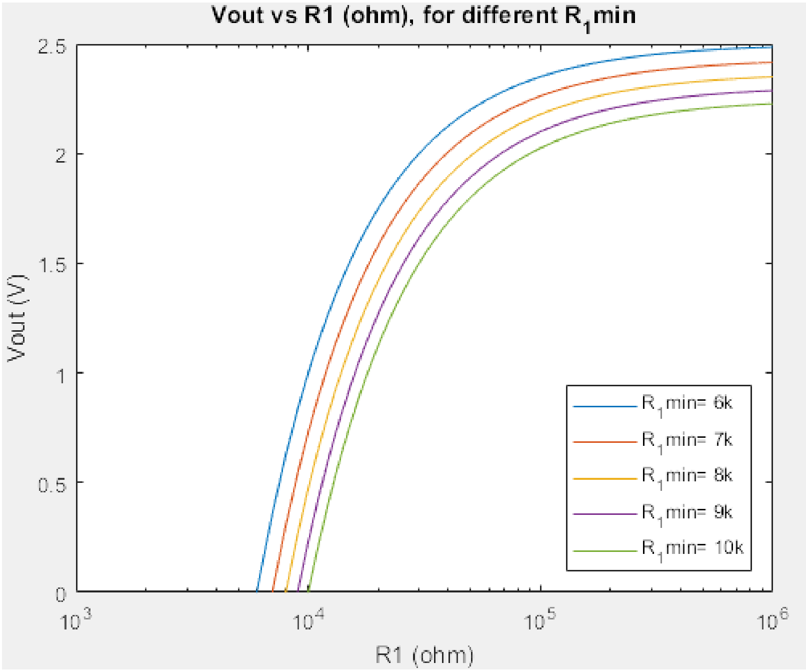


Figure 12: Plot of Vout vs R1 for different R1_min

II. Voltage Division Stage

When a fetal kick is present, an FSR from the matrix will get power through the demultiplexer, and gets connected to an output resistor in series, creating a voltage division. This stage can be implemented with or without the presence of the amplifier stage described above. The following figure shows the schematic diagram of the voltage division stage without including the amplifier stage.

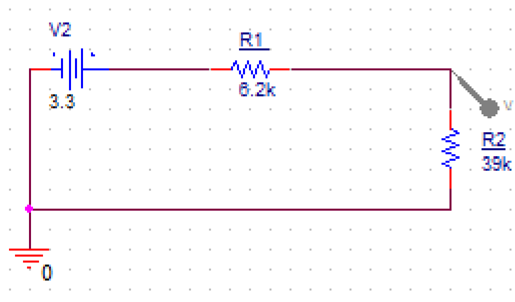


Figure 13: Schematic Diagram for voltage division stage

In the above diagram the FSR that is selected using the multiplexers due to the presence of a kick is connected in series with an output resistance. Using the equation of voltage division we can derive the equations for output voltage and sensitivity, shown in Equations (1) and (2) respectively.

$$V_{out} = V_{in} \times \frac{R2}{(R2+R1)} \quad (1)$$

$$\frac{\partial V}{\partial R_1} = -\frac{V_{DD} \times R_2}{(R_1 + R_2)^2} \quad (2)$$

The following two graphs show the sensitivity and output voltage value vs FSR resistance (R1) for different output resistance (R2) values.

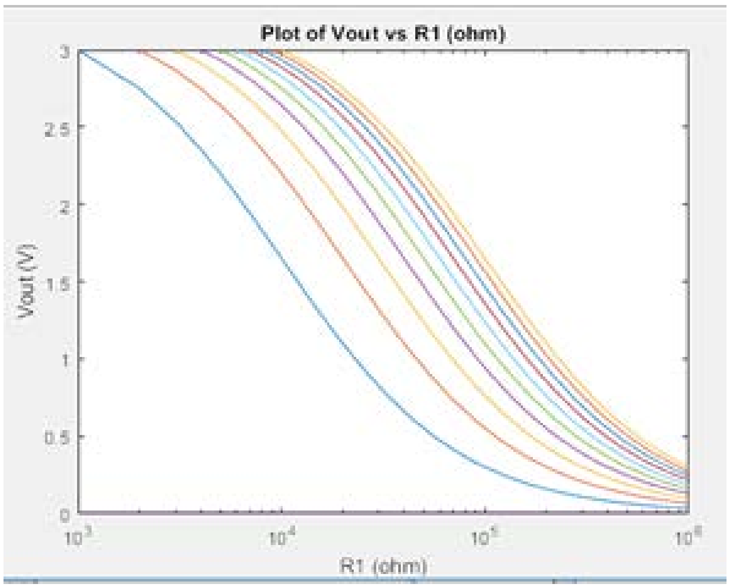


Figure 14: Output Voltage vs R1 for different R2 values

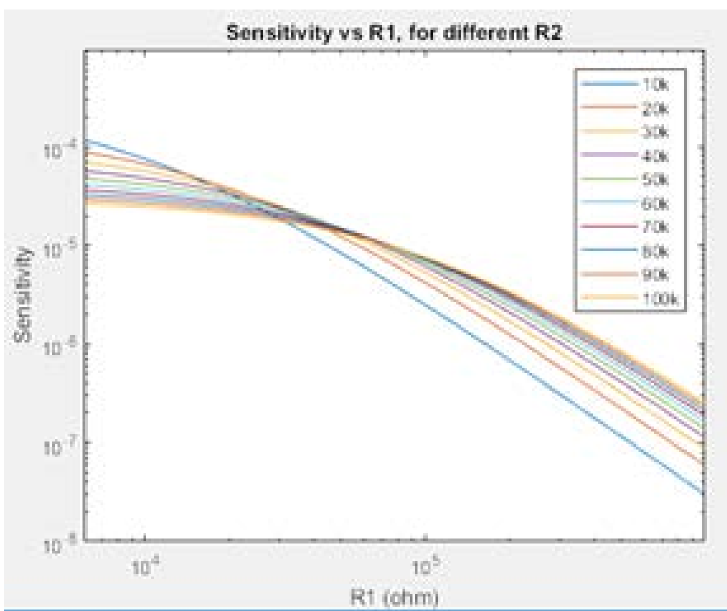


Figure 15: Sensitivity vs R1 for different R2 values

As shown in the Figure 14, the output voltage decreases as the FSR's resistance increases as expected from the voltage division equation.

As shown in Figure 15, the sensitivity of the system is higher for lower R1 values and lower for higher R1 values. Furthermore, the difference in sensitivity is significant initially and decreases as the value of R1 increases. Hence, an optimum resistance of 40kΩ was chosen for R2.

b. Simulation

I. Pre-Amplification and Amplification Stage

Based on the values we chose from modelling, the simulation of the amplifier circuit was made using PSpice software. A single FSR was connected to the amplifier based on the idea that only one FSR among the matrix of FSRs will be selected using multiplexers. The following diagram shows an FSR that is activated by an average force (0.52 N) that has a resistance value of 10 KΩ.

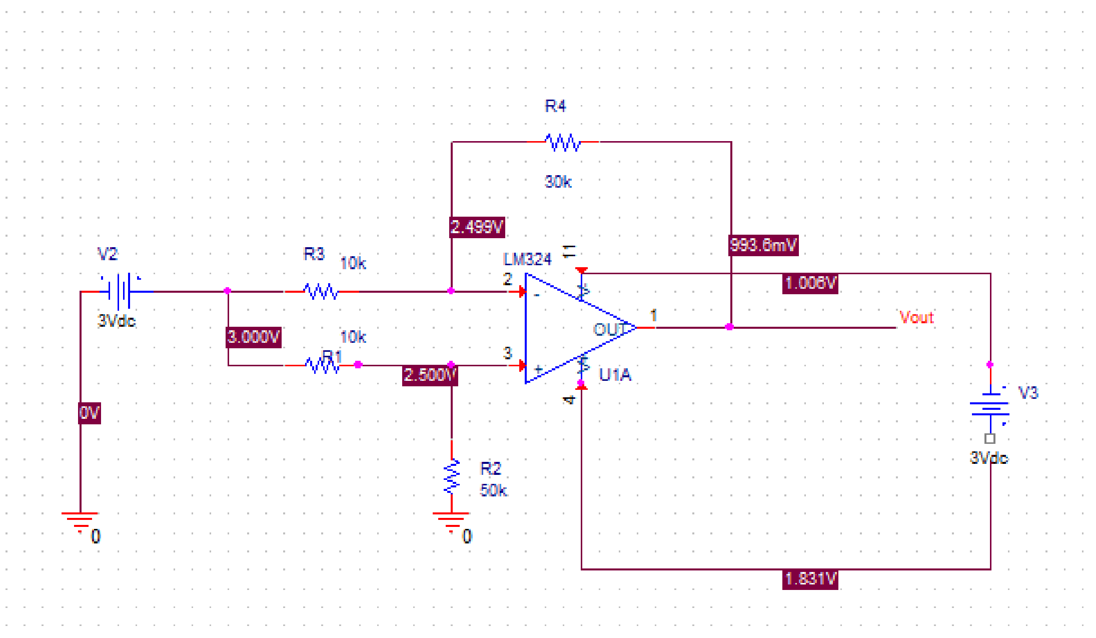


Figure 16: The amplifier circuit with simulated voltage results for 10KΩ FSR

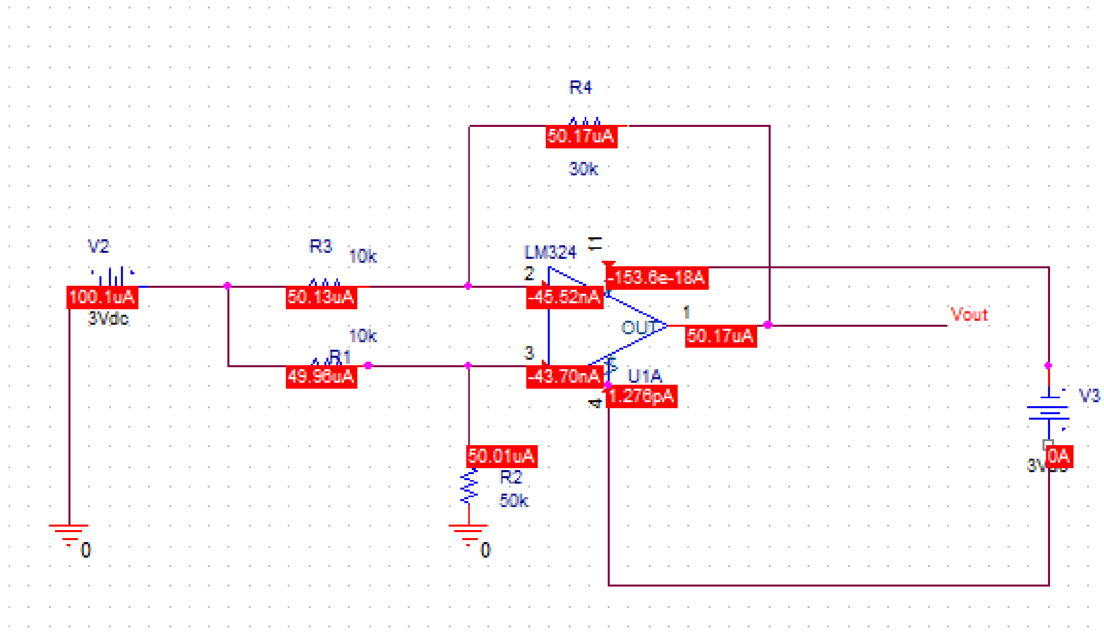


Figure 17: The amplifier circuit with simulated current results for 10KΩ FSR

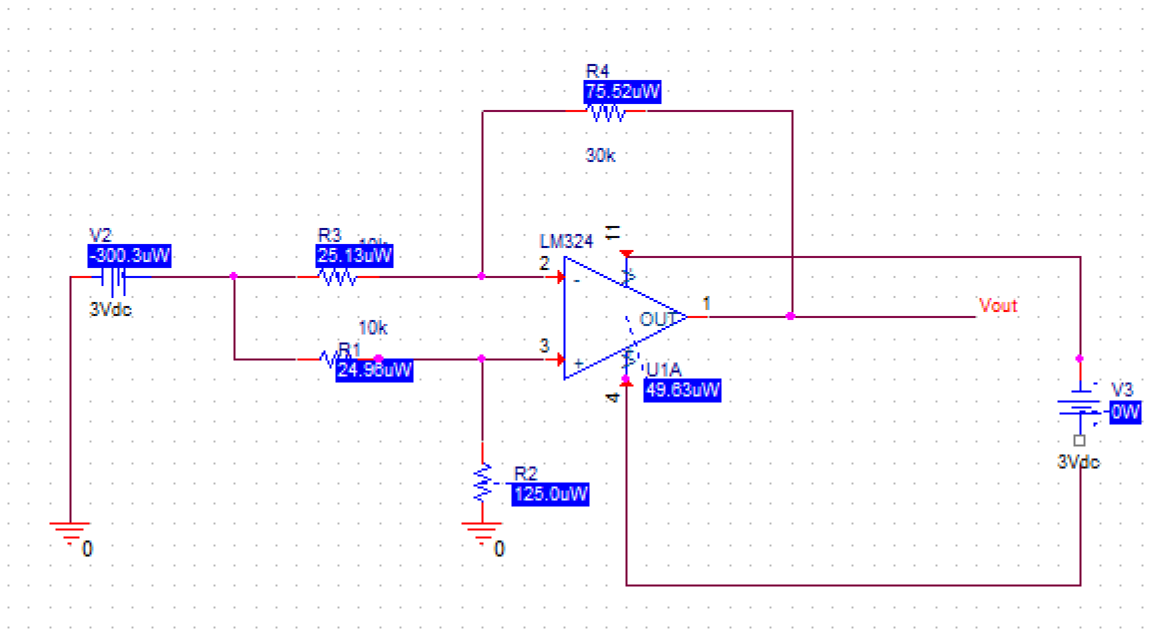


Figure 18: The amplifier circuit with simulated power results for 10KΩ FSR

The FSR value was then changed to the minimum obtainable resistance which is selected to be 6KΩ, and similar simulations were made.

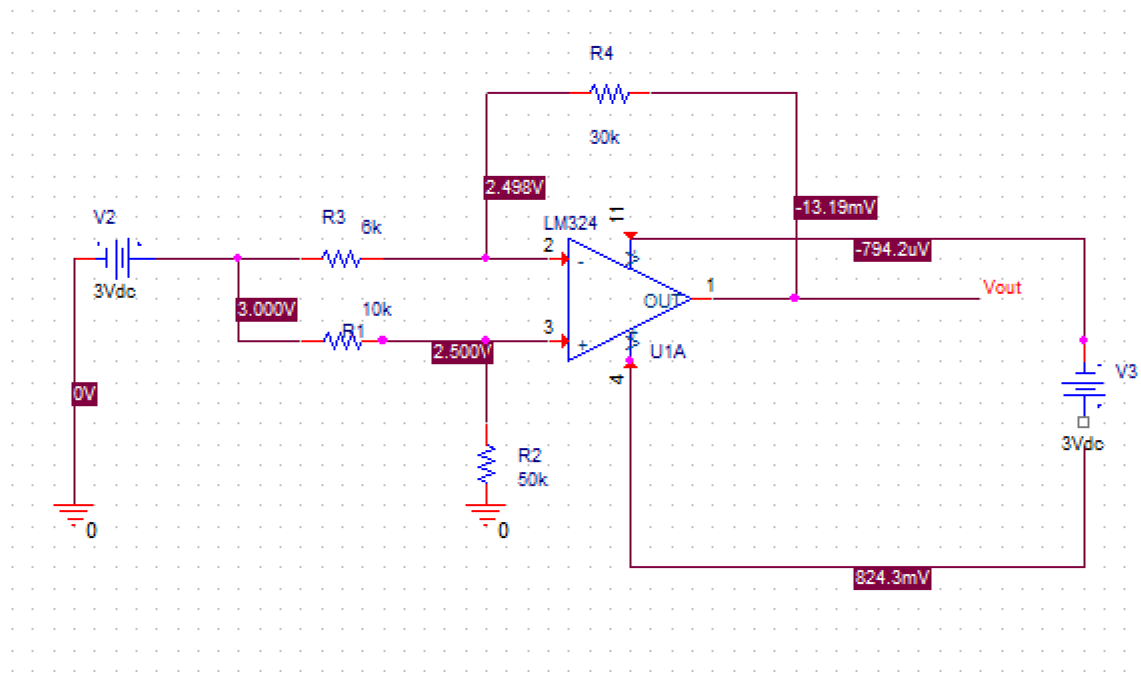


Figure 19: The amplifier circuit with simulated voltage results for 6KΩ FSR

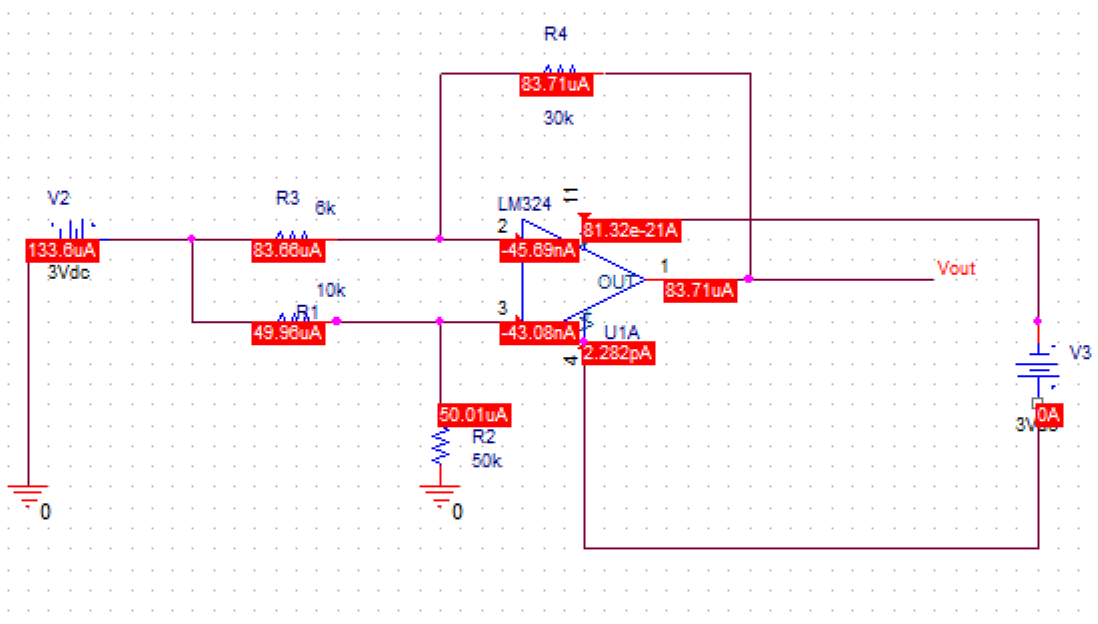


Figure 20: The amplifier circuit with simulated current results for 6KΩ FSR

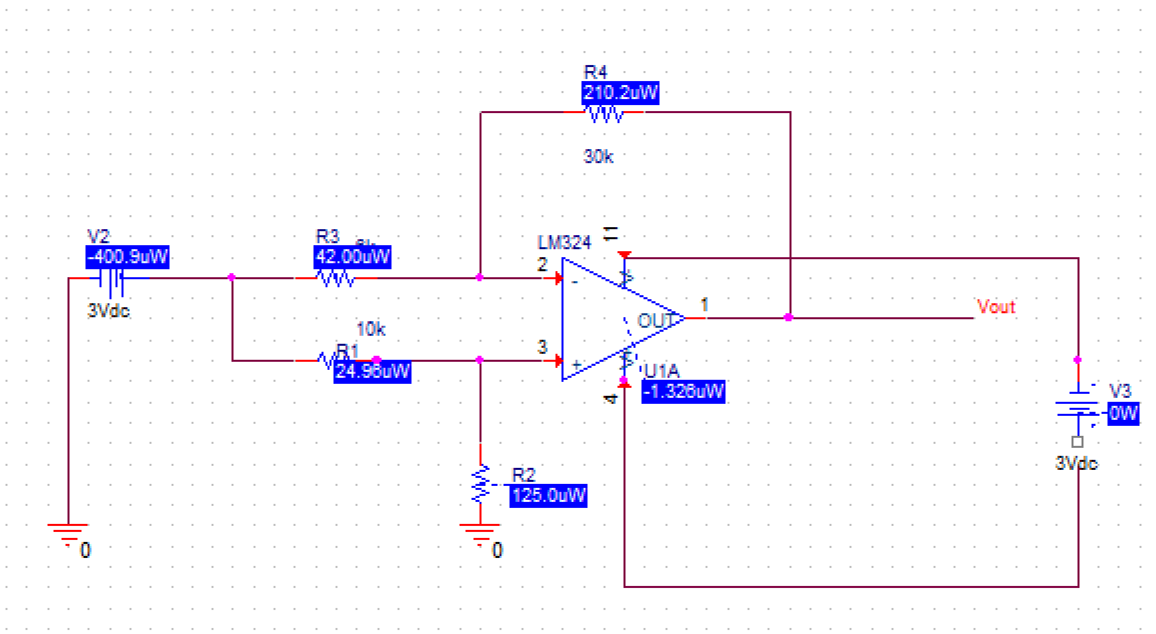


Figure 21: The amplifier circuit with simulated power results for 6KΩ FSR

The parameters of voltage, current and power were also simulated for the maximum resistance that can be resulted due to fetal kick which was selected to be 30 KΩ

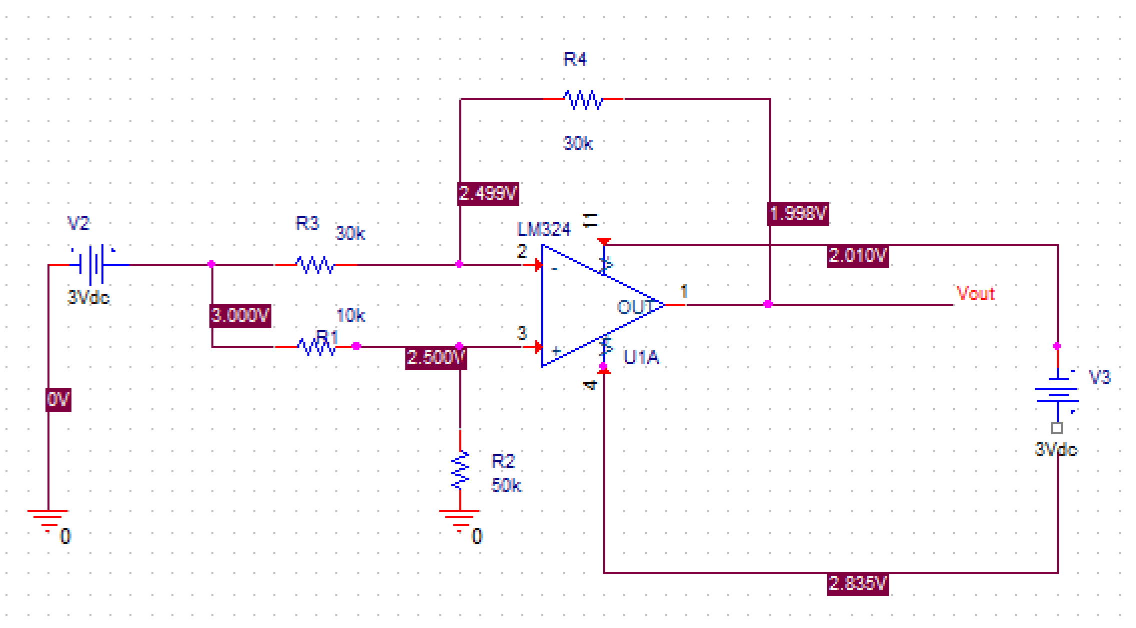


Figure 22: The amplifier circuit with simulated voltage results for 30KΩ FSR

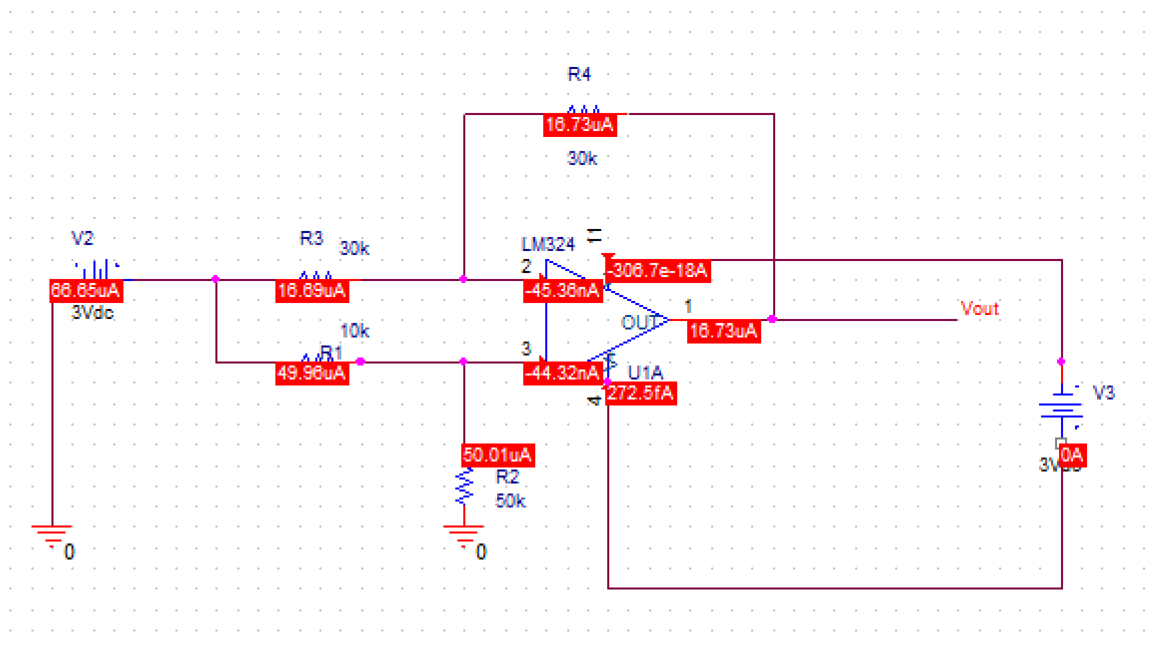


Figure 23: The amplifier circuit with simulated current results for 30kΩ FSR

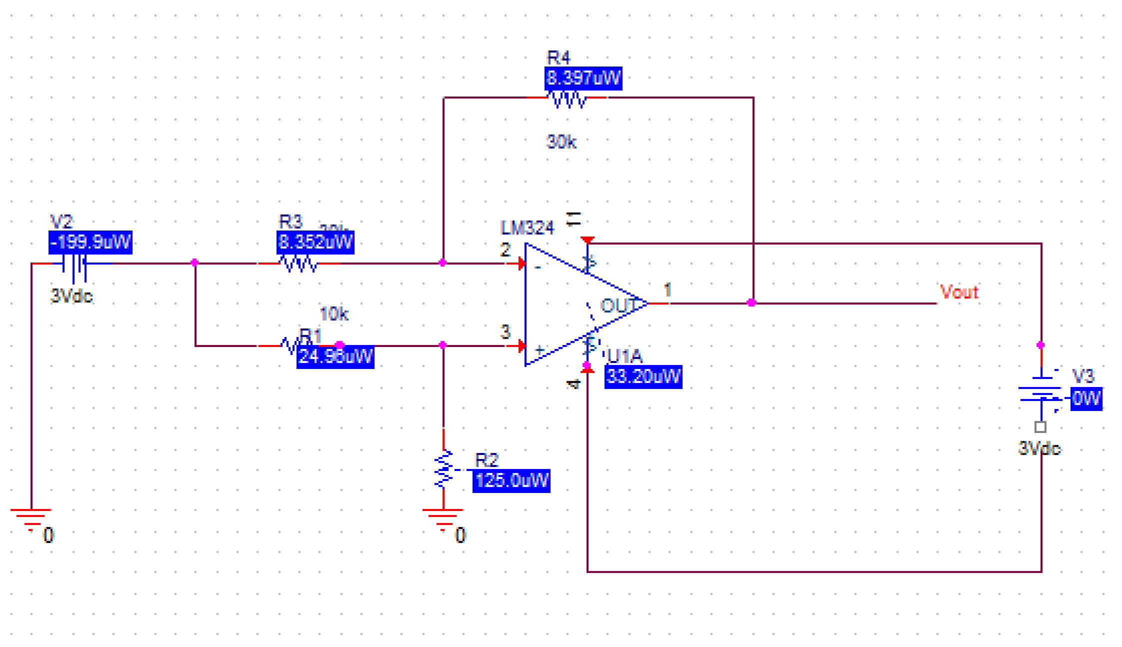
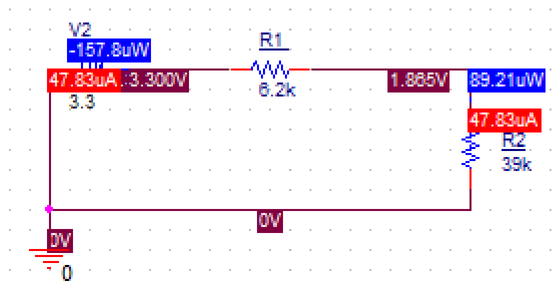


Figure 24: The amplifier circuit with simulated Power results for 30kΩ FSR

II. Voltage Division Stage

Based on the values we chose from modelling, the simulation of the voltage division stage was made using PSpice software. A single FSR was connected to the amplifier based on the idea that only one FSR among the matrix of FSRs will be selected using multiplexers. The following diagrams (Figures 25a-c) shows the voltage division of FSR that is activated by an average force (0.52 N) that has a resistance value of 6, 10, and 30 kΩ respectively.



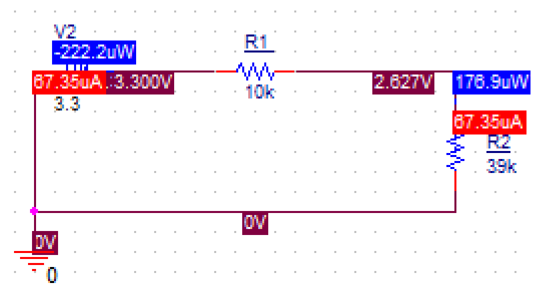
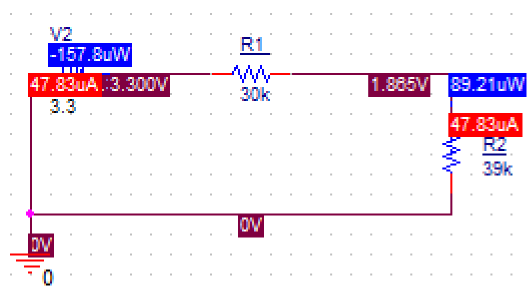


Figure 25: a) voltage division with maximum fetal force b) voltage division with average fetal kick force



c. Voltage division with minimum fetal kick force

Table 12 below shows the mapping from the resistance to the force and the output voltage obtained from the PSpice simulations.

Table 12: Relation between fetal kick force and voltage

Resistance (kΩ)	**Force (N)**	**Voltage (V)**
30	0.37	1.9
10	0.52	2.6
6	0.67	2.9

As shown in the table, lower forces correspond with lower voltage output, while higher forces give higher output voltage values.

c. Optimization and Experimentation Plan

Increasing the number of FSRs in the matrix increases the efficiency of the Automatic Fetal Kick Counter as it enables the detection of most fetal kicks. However, the power consumption increases with an increase of FSRs. Hence, an optimum number of FSR matrix must be determined through experimentation. Our experimental plan is to start with a 2 × 2 array of sensors. From previous literature reviews, the efficiency of a 3 × 3 system was determined to be 90%. By increasing the array to 8×8 force sensors, we will determine the efficiency, and analyze the power consumption.

The Matrix of FSRs will be embedded in a modified pregnancy support belt. The belt will be optimized to cover a wide area of the belly. Furthermore, an optimum distance between the sensors will be selected when placing the sensors in a matrix. The analog front-end circuit which includes the pre-amplification, the amplification, and the voltage division stages will be designed in a Printed Circuit Board (PCB) design software, and fabricated. The output data will then be transmitted wirelessly to an output display.

6. FINAL DESIGN

The Final design will consist of 8x8 matrix of Force Sensor Resistors (FSRs). FSR (model: 1027-1018-ND), preferred for its shorter wire length, will replace the sensors used in our experimentation. The sensor is shown in the figure below.

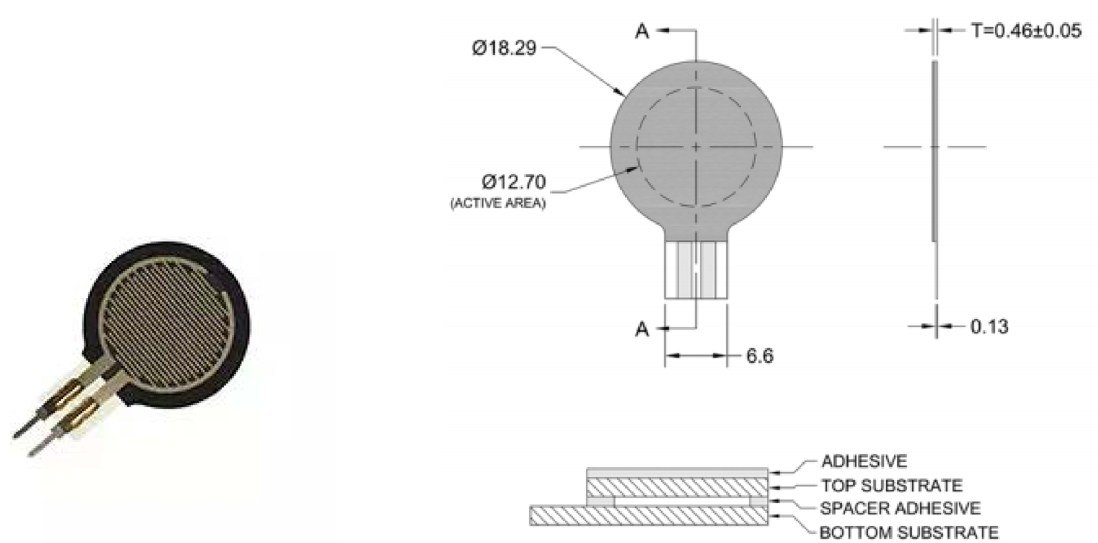


Figure 26 a) Force sensor resistor used in final prototype, b) Sensor mechanical data

The microcontroller used in the experimentation was Arduino microcontroller. For wearable and E-textile technologies the Lilypad Arduino is preferred due to its low power consumption and as it can be sewn to fabric using magnetic wire. Hence, the LilyPad Arduino will replace the Arduino microcontroller in the final design. Two multiplexers will be used to scan through the columns and rows of the matrix. A voltage division stage or an amplifications stage will follow the scanning stage. Furthermore, a low energy Bluetooth model will be used to transfer the output data to a mobile phone or a personal computer. Figure 27, below shows the end to end design of the automated fetal kick counter system.

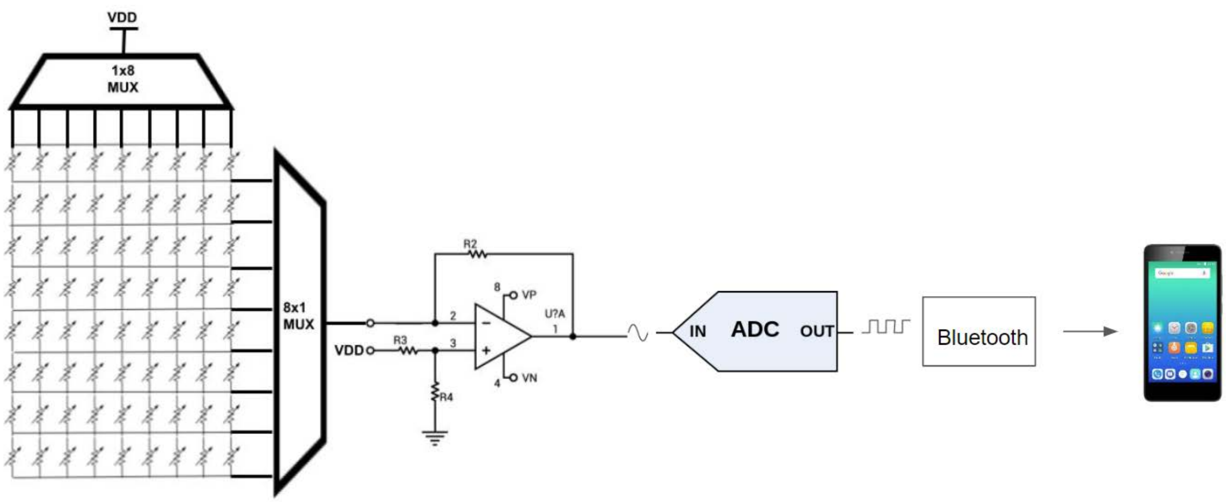


Figure 27: End-to-end system of the fetal kick-monitoring belt mechanism

7. Implementation Details

a. Success in implementing design

An 8x8 matrix was implemented using 64 Force Sensor Resistors (FSRs) on a cotton fabric which has a reasonable stretchability to account for growing belly of pregnant women. The connections for rows and the columns were made using insulated magnet wires. The implementation of the sensor matrix on the cotton fabric is shown below.

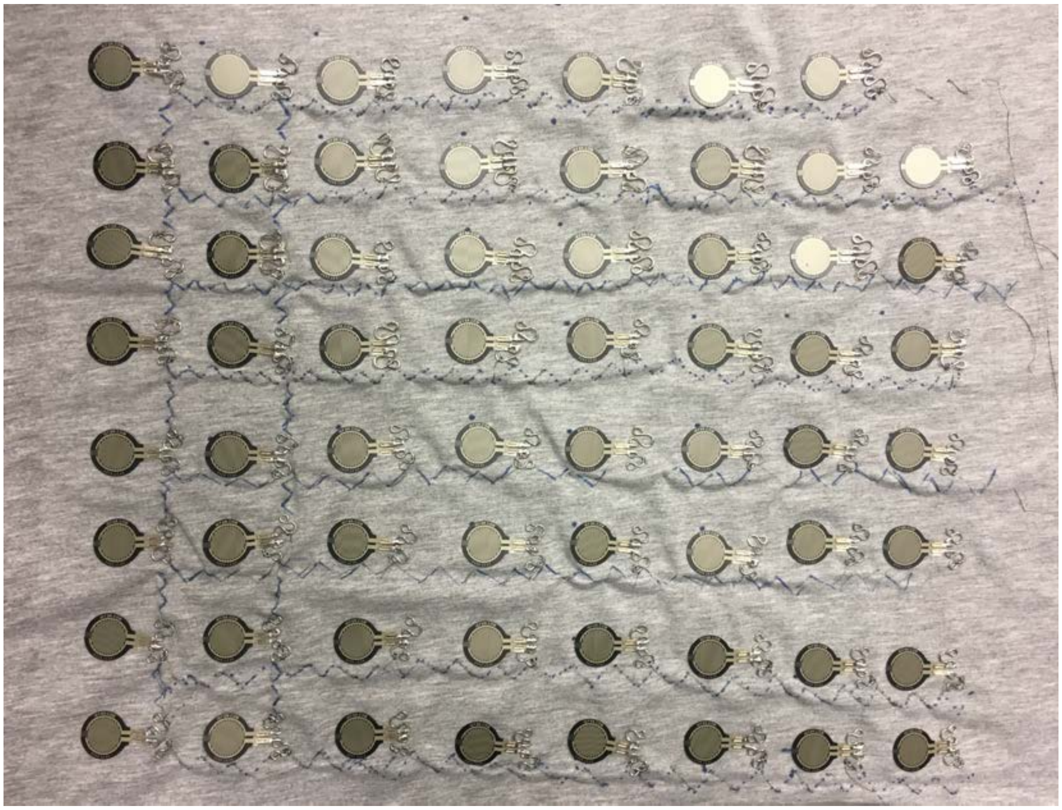


Figure 28: Implementation of FSR matrix array on a cotton fabric

A code for detecting a change on the response of the sensors was written on the Arduino Integrated Design Environment (IDE). The algorithm that was developed for checking the activation of the FSRs worked successfully. The response from the sensors was observed on the serial monitor of the Arduino.

A Printed Circuit Board (PCB) containing the selection circuitry, the voltage division, and the amplification circuit was designed using *Altium Designer* software. The design was printed successfully. The following figures shows the design on the *Altium* software, and the fabrication result.

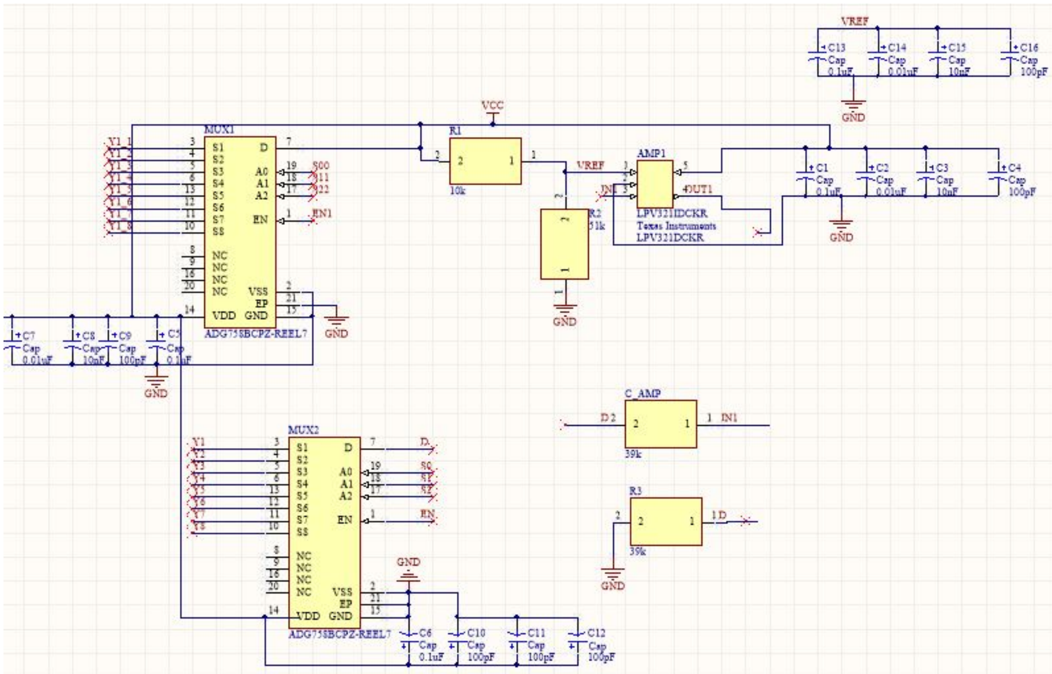


Figure 29: Schematic of circuit connection on *Altium* Designer

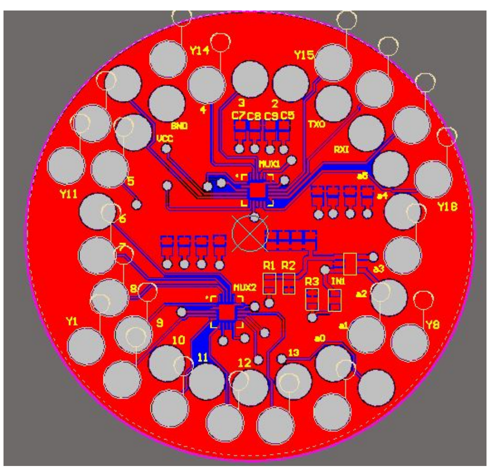


Figure 30: Routing PCB design on *Altium Designer*

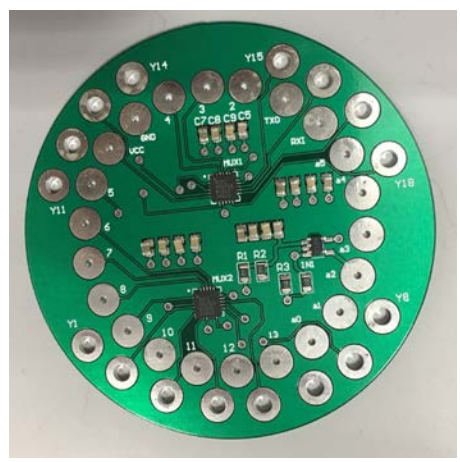


Figure 31: Fabricated PCB design

b. Issues faced during Implementation

Problems were observed while connecting the FSR sensors on a matrix form. To secure the FSRs in place, fabric eye hooks were soldered to each sensor. However, loose and a few short circuit connections were noted due to the use of exposed conductive wires that do not have insulation. Hence, observing the output of the 8x8 matrix on the computer posed an inconvenience.

Another issue was observed while trying to make the system compact. The design of the PCB was initially decided to be circular with each ports being the same as the ports on the LilyPad Arduino microcontroller, so that it overlaps with it. However, the final design could not perfectly overlap with the LilyPad Arduino due to the existence of an FTDI port in between, which is necessary for a computer interface. This issue can be resolved if the ports on the PCB are designed to be the mirrors of the ports on the LilyPad, to overlap the two boards facing away from each other as shown in the figure below.

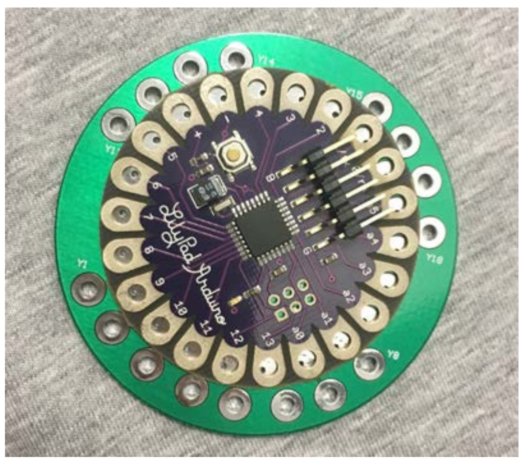


Figure 32: Desired overlap between the fabricated PCB and the LilyPad Arduino microcontroller

c. Changes made during implementation

Changes were made to some of the components used during the implementation procedure. The first component that was changed is the microcontroller. The experiment started out with Arduino Uno microcontroller. It was planned to replace the Arduino Uno with an IoT device known as CC26500 SensorTag, which has a small size. Experimentation was conducted using the SensorTag device; however, it was found to be challenging as it required reprogramming registers that were already designed for the sensors that were embedded in the system. Hence, it was decided to use the LilyPad Arduino which is smaller than the Arduino Uno and slightly bigger than the SensorTag.

The other component that was changed was the FSR. The initial sensor which has sensing area of 0.5" with a longer tail was replaced with a sensor which has a smaller tail keeping the same sensing area. Other changes that were made is replacing the conductive thread for the rows and columns by magnetic wire due to the need of insulation, and the operational amplifier used in the final design for a lower power consumption.

d. Initial Results

Preliminary experiment

During the initial stage of the experiment, a force sensor matrix array known as ThruMode Matrix array, which is a 16 ×10 matrix of Force Sensitive Resistors arranged in a grid (shown in Fig. 32 below) was tested. The matrix array covers a small area which is used for technologies that require multi sensing functionality such as various computer input devices, musical instruments, and interactive toys. The experiment with the matrix array was conducted to understand the control circuit logic which consists of multiplexers and shift registers. The figure below shows the schematic diagram of the connection used to connect the ThruMode matrix array, and a picture of the circuit connection.

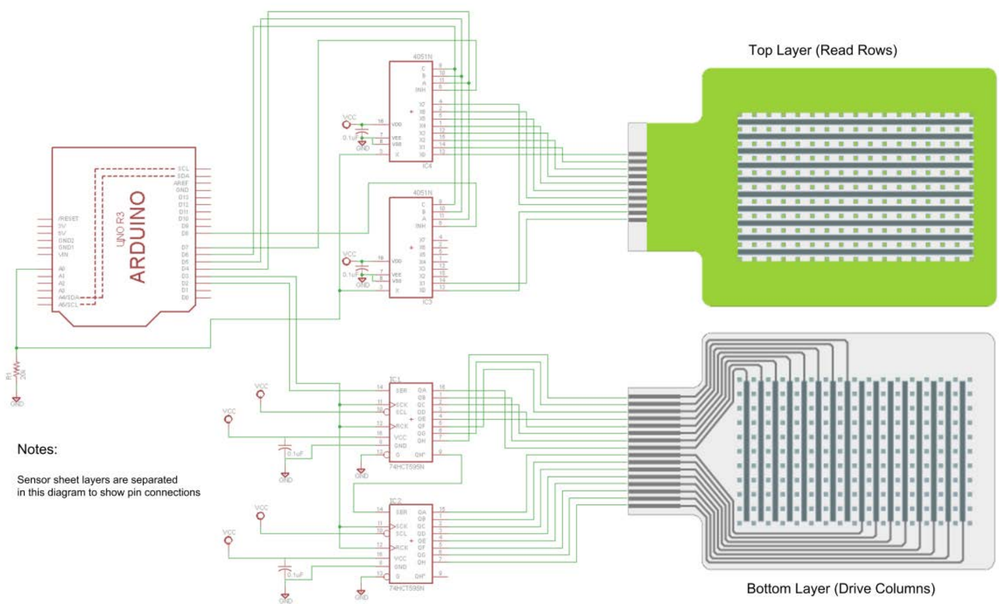


Figure 33: Schematic diagram of the ThruMode matrix array

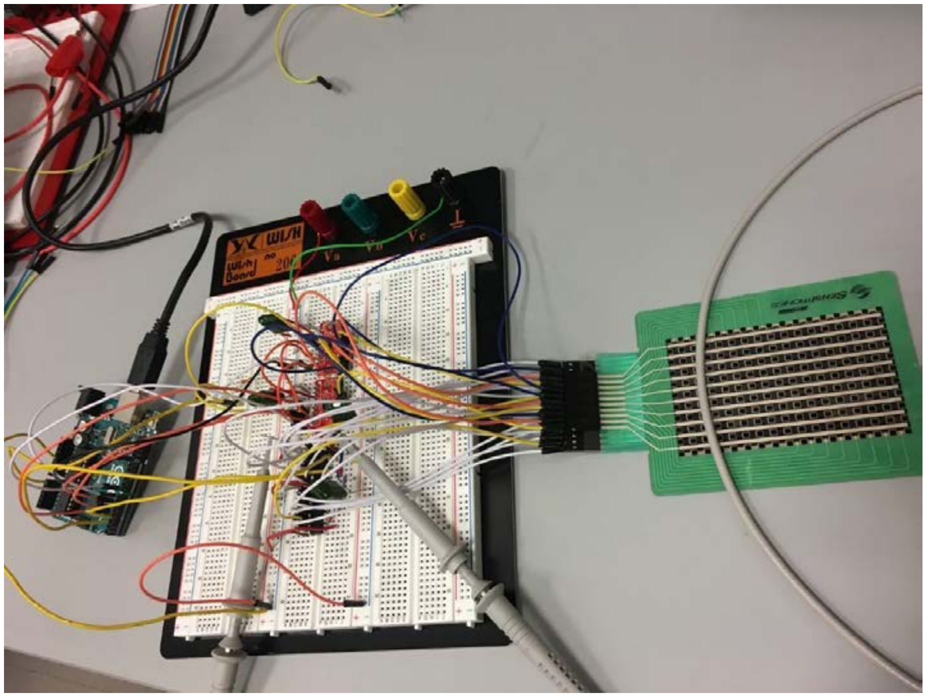
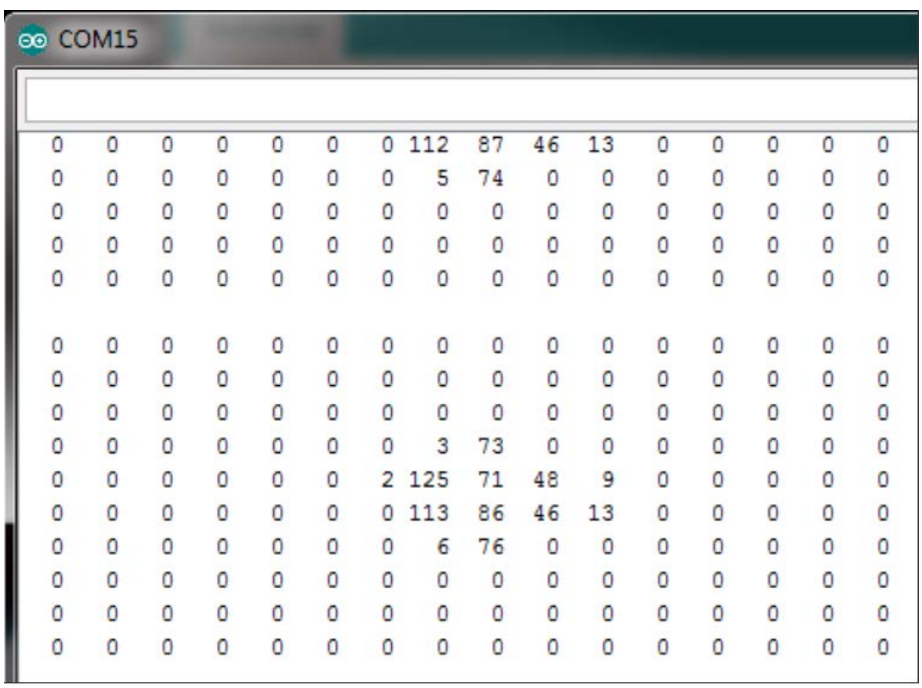


Figure 34: Experimentation using the ThruMode matrix array

The Serial monitor of Arduino IDE was used to display the values of the sensors in the presence of a force on the PC monitor on a scale of 0 to 1023. The results are shown in the figure below;


COM15

0	0	0	0	0	0	0	112	87	46	13	0	0	0	0	0
0	0	0	0	0	0	0	5	74	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	3	73	0	0	0	0	0	0	0
0	0	0	0	0	0	2	125	71	48	9	0	0	0	0	0
0	0	0	0	0	0	0	113	86	46	13	0	0	0	0	0
0	0	0	0	0	0	0	6	76	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 35: Initial result from ThruMode Matrix array

8. Ethics

The first ethical issue that needs to be addressed is safety. Current fetal monitoring systems involve the use of ultrasound to generate an image of the fetus. Although no negative associations were found between ultrasonic exposure and birth outcomes, safety concerns are still being investigate. The use of non-intrusive sensors to detect fetal kicks is proven to be a safer approach as there is no significant radiation from the electronic components. However, the final design of the Automatic Fetal Kick Counter must retain minimal contact with the electronic components to secure additional safety.

The other ethical matter is privacy in data transmission. Wearable devices transmit large amount of data which raises important ethical issue regarding security and privacy. Users will be affected if a third party accesses their confidential information in an unlawful way. Usually this happens when the data from people is needed to be sent to a third party such as clinicians to analyze the data. Since the Automatic Fetal Kick Counter is aimed to provide home-based monitoring system without sending data to hospitals, it reduces the concern of privacy.

Finally, to conduct researches regarding the needs of pregnant clients, and to test the efficiency of the product, an IRB approval is needed. Our team is in the process of applying for the approval.

9. Criteria for design, testing, and evaluation

a. Criteria for testing

- Sensitivity of sensors while testing various models of FSRs
- Testing microcontroller for accurate scanning through the matrix, and selecting the right FSR
- Power consumption when comparing two different design models (voltage divider and amplifier)
- Stretchability of fabric material when testing different fabrics for implementation
- Output data from FSR matrix
    - Correct analog output: that displays an increase in the analog output (from 0-1023) as the force increases
    - Mapping the matrix on circuitry to a matrix on the display screen of the computer
    - Accurately converting the analog output (0-1023 scale) to a force in Newtons(N)
- Replicate the system with wireless data transmission

b. Test data and Discussion

The sensitivities of different FSR models was tested, as shown in Figure 36 below. From the experimental results, it was found that the sensor with the larger sensing area (model FlexiForce A401 sensor) had a lower sensitivity compared to the 0.5” diameter sensor on the right (model: SEN-09375). Hence, the FSR with best sensitivity was chosen to be one that senses forces as low as 0.2N.

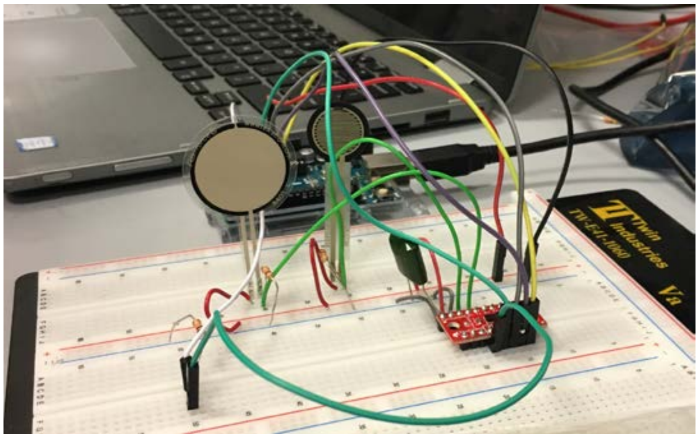


Figure 36: Comparing the sensitivities of two different FSR models

Following the comparison between the two FSRs, we proceed to compare a design that uses the amplifier stage with a one that only uses the voltage divider stage. The PSpice simulation is shown in the *Simulation* section of the report. While there was a slight improvement in the voltage gain using the amplification stage, the design that uses only a voltage division stage also resulted in a reasonable output voltage. Hence, due to simplicity and lower power consumption value, the design that only uses voltage division was selected to be implemented in the final design.

Next, a 2 ×2 matrix of FSRs was constructed to test the output of the sensors, and map their location on a matrix of a computer display. The connections were made using multiplexers and voltage divider circuit. The implementation on the breadboard is shown below.

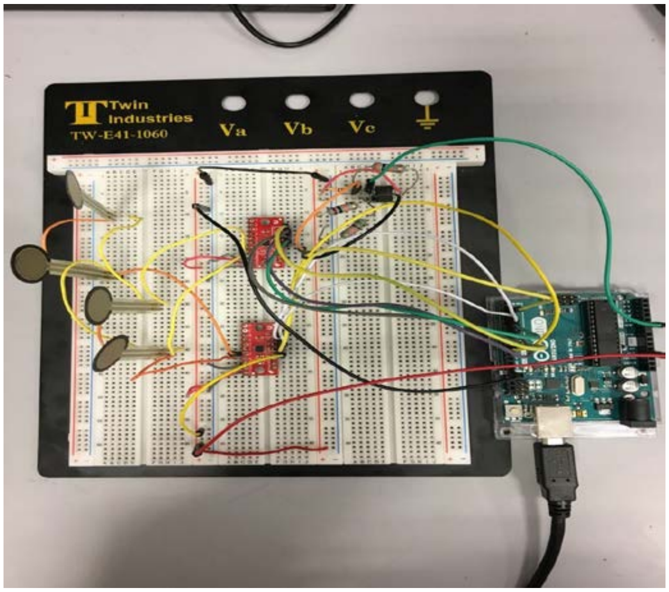


Figure 37: 2x2 matrix with voltage division stage

Following the above procedures, a 2x2 force sensors array was implemented on a fabric for a better integration into the belt prototype. We were able to successfully replicate the circuitry on the breadboard on to a fabric using conductive threads. The result was observed on the serial monitor of the Arduino software. The following figure shows the implementation.

Figure 38: Completed fabric-mounted 2x2 sensor prototype

The result of the 2x2 matrix array was observed on the serial monitor of Arduino IDE and processing software as shown in the figure below.

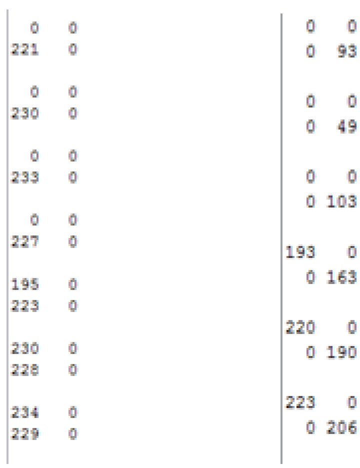


Figure 39: Screenshot of the result

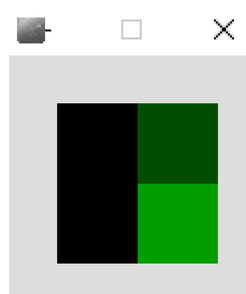


Figure 40: Display of 2x2 matrix array

Figure 39 above displays the output result when the FSRs were pressed. The position of the FSRs matches the position of the matrix on the serial monitor. The output displays the number from 0 to 1023 which is directly proportional to the amount of applied force.

To create a graphical interface processing software was used. Figure 40 shows the output on a processing software with the positions of the FSRs represented by green squares. The intensity of the color is directly proportional to the amount of force.

The output of the Arduino serial monitor is analog output ranging from 0-1023. However, this result needs to be mapped to force as the intended use of the product is to record data on the fetal force to count and analyze it. Hence, the analog output was mapped to a resistor and force value using a conversion algorithm. The result was observed on the serial monitor, and a screenshot of the force values from the FSR matrix is shown in Fig. 40 below. A counter algorithm was also developed based on a change in the FSRs output value.

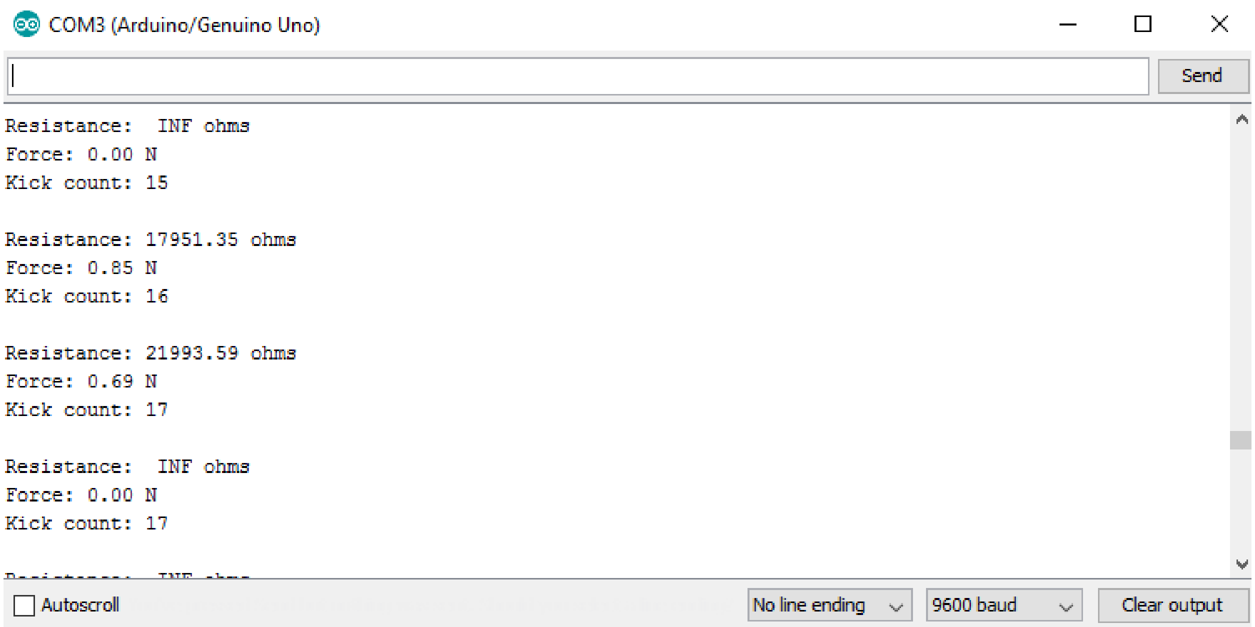


Figure 41: Converting analog output to Force (N)

Wireless transmission was tested using a Bluetooth module HC-06 for the 2 x 2 FSR matrix. The data was transmitted with a baud rate of 9600 (9600 bps) to a computer.

10. Conclusion

The force sensor resistors that were used in the final design optimized for space, as it has shorter legs which in turn allowed to increase the density of sensors, and for sensitivity. Regarding the analog output from the sensor, forces as small as 0.2 N were displayed on the serial monitor in real-time. While further tests need to be conducted with pregnant women, the Automated Fetal Kick monitoring belt met the criteria for design evaluation that were specified in the report.

Furthermore, our design effectively standardizes the fetal movement force measurements, and addresses the problem of subjectivity while monitoring fetal kicks. It saves the time spent to monitor baby kicks as it is automatic system, and permits primigravida and women with high risk pregnancy to keep track of their baby's movement in the comfort of their home.

Moreover, it allows pregnant women to detect changes in their baby's movement over time that is associated with fetal distress which enables the early diagnosis of possible complications through medical follow up.

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Appendix

Bill of Materials

No	Part	Price in $	Quantity	Total
1	Force Sensing Resistor 402 Short (model: 1027-1018-ND)	8.14	70	570
2	Breathable Adjustable Maternity Belt Pregnancy Support Belt for Belly,Waist,Back	18.8	1	18.8
3	ThruMode Matrix Array	30	1	30
4	Shift Register 8-Bit - SN74HC595	0.95	4	3.8
5	SparkFun Multiplexer Breakout - 8 Channel (74HC4051)	1.95	2	3.9
6	CR2032 3 Volt Lithium Coin	2.95	1	2.95
7	op-amp (3), model LM324	6.95	1 pack	6.95
8	LPV321M5/NOPBCT-N op-amp	0.95	5	4.75
9	Magnet wire (model: MW35-C HY 34AWG 1KG/2.2LBS)	75.16	1	75.16
10	Sunstone circuits - PCB fabrication	39.45	4	157.8
11	Conductive Thread Bobbin - 30ft (Stainless Steel) DEV-10867	2.95	3	8.85
			Total	882.96