HEART AND LUNG SOUND SENSING SHIRT

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Abstract

The purpose of our device is to record heart and lung sounds using an array of 6 digital microphones daisy-chained with each other. The microphones have a common clock signal SCK, word select WS as well as data bus SD and each microphone outputs data on the bus depending on WS, which also sets our audio sampling rate. The microphones are placed on the lower rib cage for recording lung audio and on the chest region for heart audio. Ambient noise is removed from our raw audio using an Adaptive filtering Unit and it is then converted to WAV file format. Finally, after recording audio for a minute, WAV files are transferred to a microSD card for user access.

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1. Introduction

According to the World Bank and WHO, half the world lacks access to essential health services and 100 million are pushed into extreme poverty because of health expenses. There are many factors for this such as the lack of good doctors and the poor quality of medical diagnostic devices. Often, this causes people to travel large distances to talk to a doctor, which can be hard. Even after investing time and money, they might not be able to get good quality treatment. In this case, many people would benefit if they had were able to consult a doctor without physically going there. This inspired us to take on a senior design project that may potentially solve this problem.

Our goal is to design and build a shirt that is capable of detecting heart and lung sounds which a user can access on his smartphone and then send to a professional doctor. Therefore, this project will provide convenience for many people and cause them less stress when the need to see a doctor arises. In the market, there are shirts that can detect a user's breathing and heart rate. Other products like Littmann Electronic stethoscopes offer good biological sound detection, but do no capture the sounds from different areas in the body at the same time like our device. These stethoscopes are also significantly expensive than standard auscultation devices as well as our product. This shirt will detect the sounds of both the heart as well as lung and by interfacing the SD card with a microcontroller. The sounds can be accessed by the user on a smartphone and sent to a doctor for analysis. Figure 1 describes how different blocks in our system interact with each other.

We will be discussing the design decisions, our challenges, as well as testing and verification of the various components of our system. Our intended goals were that the microphones must be able to record heart sounds between 60 - 250 Hz as well as lung sounds between 50 - 2500 Hz with a Signal-to-noise ratio of 20 dB, the 24-bit, 16 kHz WAV files* generated should contain low-noise audio and the doctor should be able diagnose the patient's medical condition in at least 69% of cases [], which will make it as good as high-end stethoscopes.

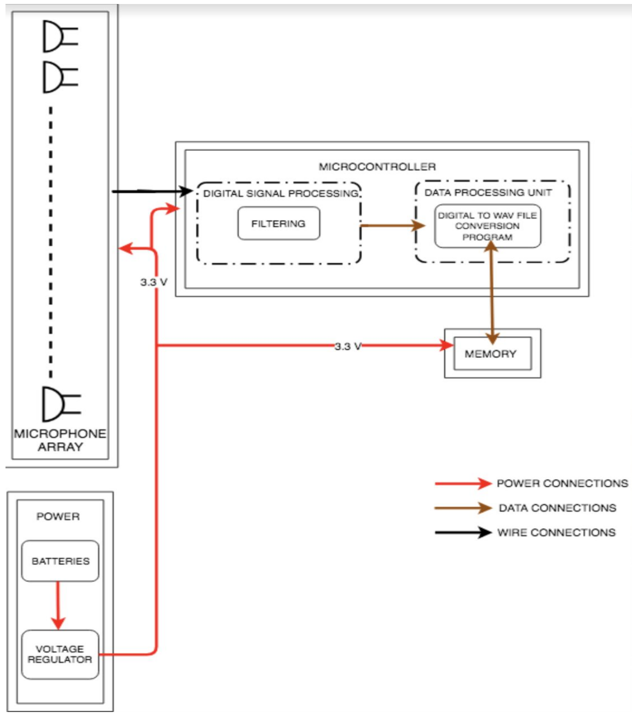

Figure 1: Block diagram of our system showing how hardware and software interact with each other

1.1 Background Information

An important component of our project is the Adaptive filtering Unit and how we characterize different sounds. During the course of this project, we discovered that the majority of noise when recording heart sounds comes from the lungs and vice versa. So, to record our contaminated heart sounds, we choose to place our microphone boards at Aortic, Pulmonic as well as Mitral area and the ambient lung noise is collected from lowermost region of the rib cage. Similarly, to record our contaminated we place the microphone boards at the lowermost region of the rib cage and record ambient heart noise at the Aortic area.

2. Design

2.1 Design Procedure

2.1.1 Power Unit

Our decision was motivated by our intention to make the shirt disposable and an alkaline 9V battery allowed us to achieve this goal without our device posing a great environmental hazard. A layer of cloth placed between our circuit with the battery holder as well as the associated circuitry and the user is ideal to achieve user safety. The microphones and the microcontroller were also chosen to be low-power.

2.1.2 Microphone Array

The microphones are the sensors used to record audio in our system. We chose Invensense ICS-52000 digital microphone ICs because of their compact size as well as their ability to be daisy-chained and output audio data on a single data bus. We wanted microphones that must be able to record heart sounds between 60 - 250 Hz as well as lung sounds between 50 - 2500 Hz and the wide frequency response from 50 Hz to 20 kHz of these microphones made them ideal for our design.

2.1.3 Microcontroller

For this project, we needed I2S interface to get audio samples from the microphones, an adaptive filtering unit to filter heart as well as lung sounds and an SPI interface to write data to the microSD card. For such purposes, the microcontroller needs to have dedicated I2S and SD card SPI hardware. On the software side, it also should allow us to have the ability to easily implement an Adaptive filtering unit.

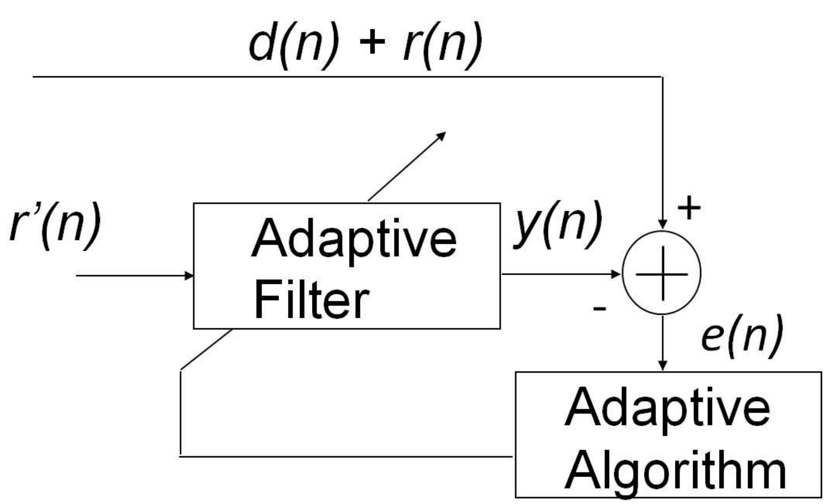

Figure 2 : LMS noise cancelling filter implementation

2.1.4 Microphone circuit

This circuit serves to interface the microphones to the microcontroller and power unit.

2.2 Design Details

2.2.1 Power Unit

We used a 9V battery interfaced with Low-dropout regulator outputting 3.3V to power all the systems in our circuit. When our circuit is powered up, the red LED, interfaced as shown in Figure 2 , turns on.

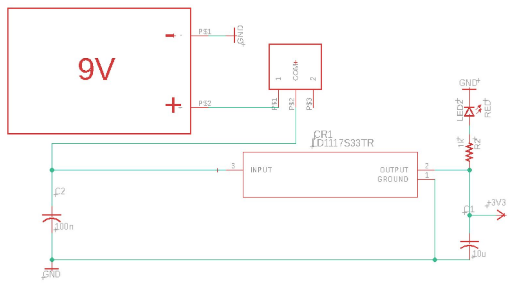

Figure 3 : 9V battery interfaced with LDO chip

2.2.2 Microphone Array

The microphone array is interfaced with the Main circuit consisting of the Power Unit, microcontroller and microSD card using an array of connectors as shown in Figure 3 . The WSO of each microphone is connected to the WS of the next microphone in the array to allow synchronous audio sampling. The WSO of the last microphone in the array is unconnected.

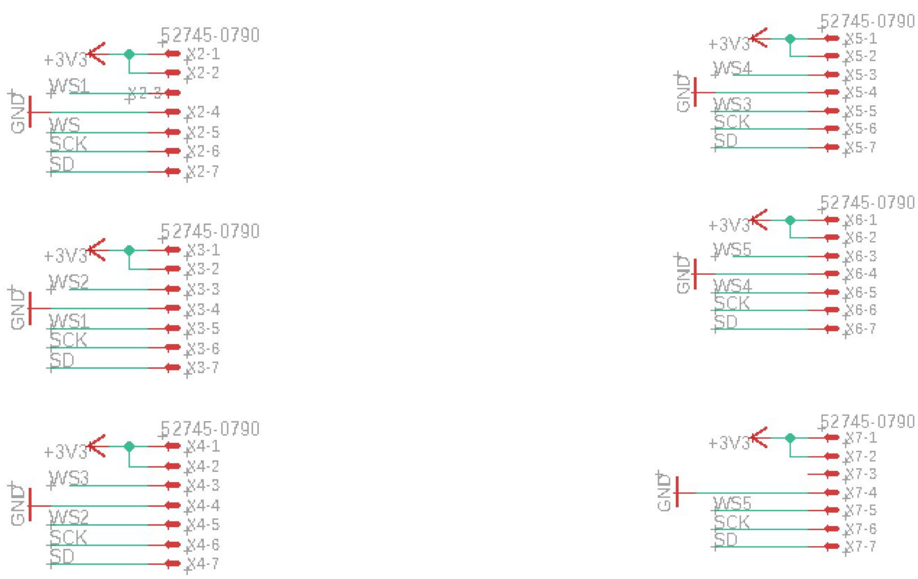

Figure 4 : Connector array for microphones on main circuit board

2.2.3 Microcontroller

The main clock frequency of the microcontroller should be divided to obtain our desired sampling rate. In our case, we had 16 kHz WS and a 48 MHz clock, which means we needed a clock divider of 48 Mhz/16kHz = 3000. Based on WS, our microcontroller generates a SCK frequency of 32*8*16kHz = 4096 kHz. To program the microcontroller, we used SWD connector interfaced as shown in Figure 4 . The microSD SPI interface is also shown in Figure 4.

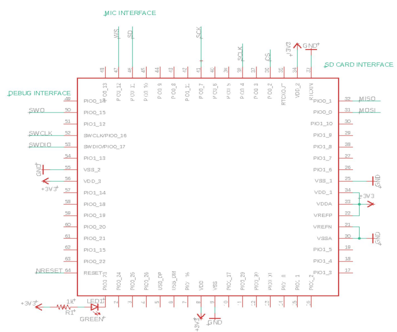

Figure 5: Microcontroller interfaced with microSD card, microphone array and power circuit

2.2.4 Microphone circuit

This circuit connects the VDD, CONFIG, WS, SCK, SD and GND pins to the respective pins on the main board using jumper cables.

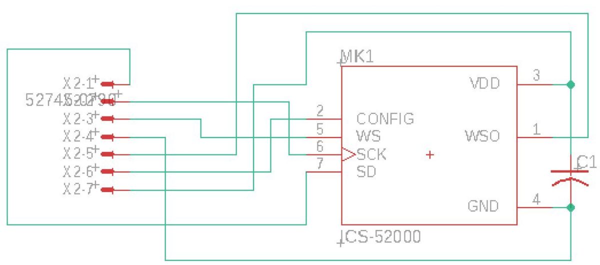

Figure 6 : Microphone circuit board schematic

2.2.5 Main board Layout

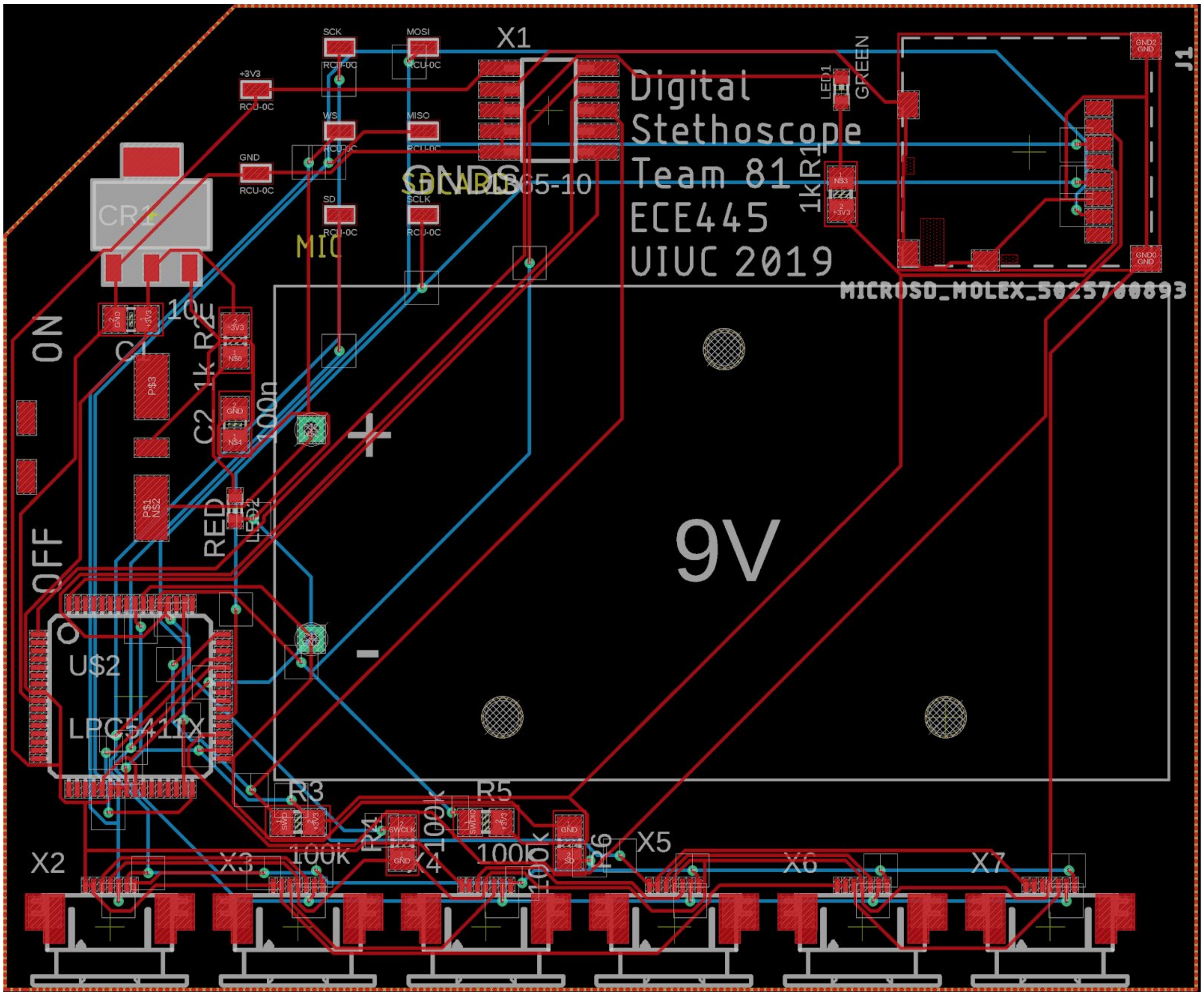

Figure 7: PCB layout for main circuit

3. Test Plans and verification

3.1 Microphone array

To verify the operation of the microphone array, we generate a sine sweep over the frequency range of the the microphones and save the sampled data to a file. We then perform a frequency analysis of the data in matlab and check that the magnitude frequency response is constant over the frequency range of the mics.

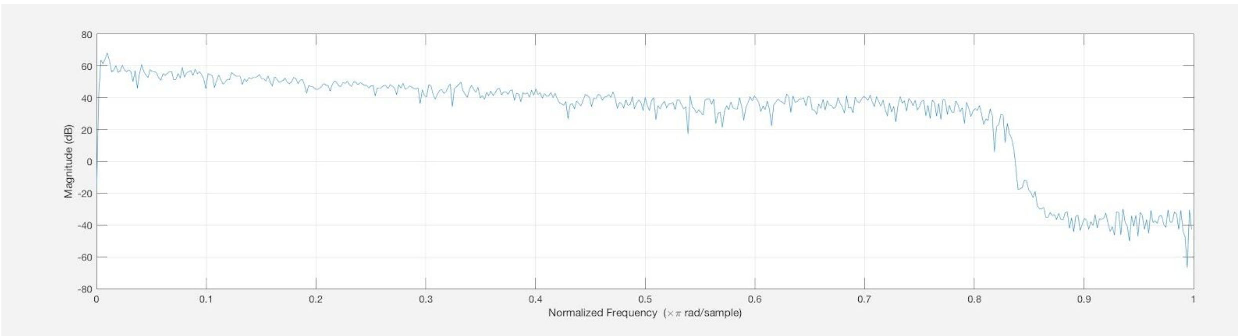

Figure 8: freqz() plot of sine sweep response

Pictured above is the magnitude frequency response of one of the ICS-52000. The magnitude remains relatively constant until the normalized frequency reaches 0.8 radians. At our specified test sampling frequency of 48kHz, this corresponds to a 0.8/2*48kHz=19.2kHz -3dB corner frequency, falling 800Hz below our requirement. However, our system is designed to process a maximum of 2500Hz, so the microphones are sufficient to capture the data required by subsequent blocks in our system.

3.2 Power Supply

In order for the the power supply to keep the components in our system operating, the voltage output by our low dropout regulator (LDO) must always be 3.3V$\pm$.1V. To verify this, we probed the 3.3V test point while loading the output of the regulator with a 5Ω 1/4W resistor drawing 0.66A of current, exceeding the maximum current draw of our entire system. 3.25V were measured, so our power system meets our requirements.

3.3 Digital Filter

To verify our digital filtering block works, we play broadband noise through a speaker to the environment, and capture both filtered and unfiltered data through the debug console. Comparing the frequency spectra in MATLAB for the filtered and unfiltered signals, we see the overall signal power reduced for the the filtered plot, while still being able to clearly hear heart and lung sounds using soundsc().

3.4 WAV File Storage

To test SD card functionality, we test the FatFS API functions by calling finit(), fmount(), fopen(), fread(), and fwrite() to write and read a simple text file to the SD card.

```
Initializing SD card...initialization done.
Writing to test.txt...done.
test.txt:
testing 1, 2, 3.
testing 1, 2, 3.
testing 1, 2, 3.
testing 1, 2, 3.
testing 1, 2, 3.
testing 1, 2, 3.
testing 1, 2, 3.
testing 1, 2, 3.
testing 1, 2, 3.
```

Figure 9: console output indicating successful read/write to/from sd card

Requirement	Verification	Met?
Microphone block ● Have a Frequency response in the range 50 Hz - 20 kHz. ● Operate on 3.3 V +/- 0.1 V.	● A stepped sine sweep is played from 50 Hz to 20 kHz through a source and the raw audio samples can be recorded using the microcontroller with a sampling rate of 48 kHz. The Frequency response can be plotted from the obtained data. ● Power the microphones with voltage in the range 3.2 V - 3.4 V.	Yes
Power Supply ● Generate 3.3 V +/- 0.1 V. ● Can operate at currents 0-100 mA. ● Batteries provide 1000 mAh of power.	● Measure the output voltage from the voltage regulator and ensure that it stays within the 3.2 - 3.4 V range. ● Use a constant current circuit to draw 100 mA from the power supply and voltage regulator. ● Ensure that the batteries run for 10 hours at maximum current (100mA).	Yes
Digital Filtering ● -3 dB Frequency Response below 60 Hz and above 250 Hz for filtering heart sounds. ● -3 dB Frequency Response below 50 Hz and above 2500 Hz for filtering lung sounds. ● Microcontroller should generate 16 kHz WS signal [6]. ● Microcontroller should generate 4096 kHz SCK signal [6] ● Startup time to valid data is 256 ms [6].	● Generate stepped sine sweep* from 0- 60 Hz and record the audio samples using the microcontroller. Measure Frequency response to verify it is -3 dB below. Repeat the process for signals 250 Hz and above by generating sine sweep from 250 to 2500 Hz. ● Generate stepped sine sweep* from 0- 50 Hz and record the audio samples using the microcontroller. Measure Frequency response to verify it is -3 dB below. Repeat the process for signals 2500 Hz and above by generating sine sweep from 2500 Hz to 3500 Hz . ● Verify the frequency of WS signal using oscilloscope. ● Verify the frequency of SCK signal using oscilloscope. ● Run code to capture data 256 milliseconds after initial power up and ensure 1 raw audio sample corresponding to $1/(16 \times 10^3)$ seconds = 0.0625 milliseconds is captured.	
Wav File Conversion ● WAV file conversion of the raw audio sample. ● Processes only 4 WAV files at a time and stops conversion right after.	● Run a raw audio sample through the data conversion code and ensure output is a 24 bit, 16 kHz WAV file. Verify the sampling rate corresponding to the WAV file using MATLAB. ● Convert four 1-minute audio samples to WAV files and check if exactly 11.25 MB SD card memory was used.	Yes

4. Costs

4.1 Parts

Description	Manufacturer	Model #	Units	Units cost	Total
Microcontroller	NXP	**LPC54114**	1	$6.55	$6.55
Microphones	Invensense	**ICS - 52000**	10	$2.85	$28.5
SD card	SanDisk	**SDSDB-128**	1	$9.98	$9.98
Resistors	Various	**Various**	6	$0.10	$0.6
Capacitors	Various	**N/A**	12	$0.30	$3.6
Voltage Regulator	STMicroelectronics	**LD1117**	1	$1.95	$1.95
PCB	PCBWay	**N/A**	1	$100	$100
Connectors	Molex	**54765-0790**	6	$0.36	$2.16
9V battery	Duracell	**MN1604**	1	$6.65	$6.65
Jumper cables	Molex	**0152670249**	6	$1.00	$6.00
Total Cost					$165.99

4.2 Labor

Our fixed developmental costs are about $40/hr, 10 hrs/week for three laborers.

$$\frac{\$40}{1\ hr} * 2.5 * 10\ weeks * \frac{10\ hours}{1\ week} = \frac{\$10{,}000}{laborer}$$

Considering we have 3 laborers, our total labor cost is,

$$\frac{\$10{,}000}{laborer} * 3\ laborers = \$30,000.$$

5. Conclusion

5.1 Accomplishments

We were able to fully integrate and test our hardware. We also were able to successfully interface the microphones with the microcontroller and print audio data.

5.2 Ethical considerations

The first safety concern is the potential heat generated by the battery. We have ran tests on the circuit to understand this hazard and fortunately our circuit doesn't heat up when left on for long hours possibly due to low-power components in the design. We still cannot ignore this hazard and should run more rigorous tests to ensure that the user is safe from heat generation.

Another safety concern is the accuracy of heartbeat audio. Once our system is fully integrated, we have to test it on different patients and figure if it fails to detect certain conditions. We need to address this concern by rigorous testing and document the device's shortcomings.

5.3 Future work

The PCB we had for our final design was without soldermask and this is one thing we have fixed since our demonstration. The new PCBs are more robust and it is hard to short the components on the new board. We would also like to get our WAV files on the SD card instead of using raw audio samples to generate WAV files on MATLAB.

6. References

[1] TDK InvenSense., " Low-Noise Microphone with TDM Digital Output", ICS-52000 datasheet,
April 2017.

[2] TDK Invensense., " I2S/TDM Output MEMS Microphone Flex Evaluation Boards", ICS-52000
datasheet, April 2017

[3] " A. Paulson, "Institutional Review Board (IRB)," American Public University System (APUS),
09-Mar-2017. [Online]. Available:
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