University of Illinois at
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ECE 445 Team #14

Child Development Sensor
Project Proposal

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1 Introduction

1.1 Objective

Human interaction at early development stages is vital to the growth of young children. It is therefore imperative that studies be conducted on the interactions between children and their parents, most often the predominantly influencing caregivers during early development. Modern research in child development is vast. There are countless, dynamic variables in a child's early developmental period that set children on trajectories of psychological adjustment which can be difficult to alter. Although studies are expansive, the method of current research is limited[1]. Although development is dependent on repeated real-time interactions with caregivers over large amounts of time, research observations in the lab occur in short, predetermined intervals. Development cannot accurately be assessed in isolated, static interactions. Additionally, many modern development observations occur within a controlled laboratory setting however growth is intimately tied to settings such as homes and classrooms. On occasions where research is conducted in natural context, assessments are brief and researchers must be present. Due to these limitations, research methodology must be advanced through innovation.

The goal of our project for Senior Design is to develop a device that allows researchers to obtain accurate data on child development. To overcome the limitations of research occurring in controlled environments, we will be developing a wireless device that can capture and transmit accurate data to a smartphone or a memory stick. This eliminates the limitation for researchers to be present during data collection. Caregivers are able to place the device on the child and conduct studies at home or classrooms, locations where multiple repeated interactions occur, as opposed to in a controlled laboratory setting. Therefore our device would enable accurate assessment of childhood behavioral and physiological development. We will be corresponding with a mechanical engineering team to design this device. The tasks have been broken up into the following: We, the electrical team, will design the sensor network, the wireless data handling/transmission, the electrical safety of our designs, and the storage of the data. The mechanical team will be tasked with designing the housing of the electronics, the form factor of the sensing device, and the physical safety precautions necessary when in contact with children such as overheating and motion. This is a joint multidisciplinary effort advised and sponsored by Professor Harley Johnson, UIUC MechSE, and Professor Nancy McElwain, UIUC HDFS.

1.2 Background

The research on Childhood Development is extensive and complex due to many influencing variables in a child's environment. To obtain valuable data to assess a child's development, physiological, psychological, and behavioral patterns must be studied. Information such as a child's heart-rate variability[2][3], body temperature and movement, quality of sleep[4], and characteristics in pitch of a caregiver's voice[5][6] are all useful information in determining a child's growth and influencing factors such as stress. The main parameters we will be obtaining in our Senior Design project will be cardiac vagal tone, through an electrocardiogram waveform, and voice analysis through a microphone.

We will be obtaining an ECG and a voice recording of the research subject. The data will be processed and wirelessly sent to a memory storage for ease of research accessibility. Ultimately the goal is to have accessible research data unobtrusively obtained in a natural environment. The ECG sensor and probes and the microphone will be characterized and optimized for the accuracy specifications determined by the researchers. The wireless communication will be designed and information will be successfully received and accessible by researchers. Power electronics will be designed to power various circuit components in our device. We plan to deliver a working prototype of the electrical components by the end of our work for Senior Design.

1.3 High-Level Requirements

1. Obtain accurate and synchronous ECG and voice data on research subjects.
2. Wirelessly transmit sensor data in accessible format to a cloud server so that users can access it from anywhere with an internet connection.
3. Develop and implement sensor hub (ECG sensor, voice recorder, Bluetooth module, battery source) and main hub (microcontroller, Bluetooth + WiFi module, power electronics) components that fit form factor constraints.

2 Design

2.1 Block Diagram

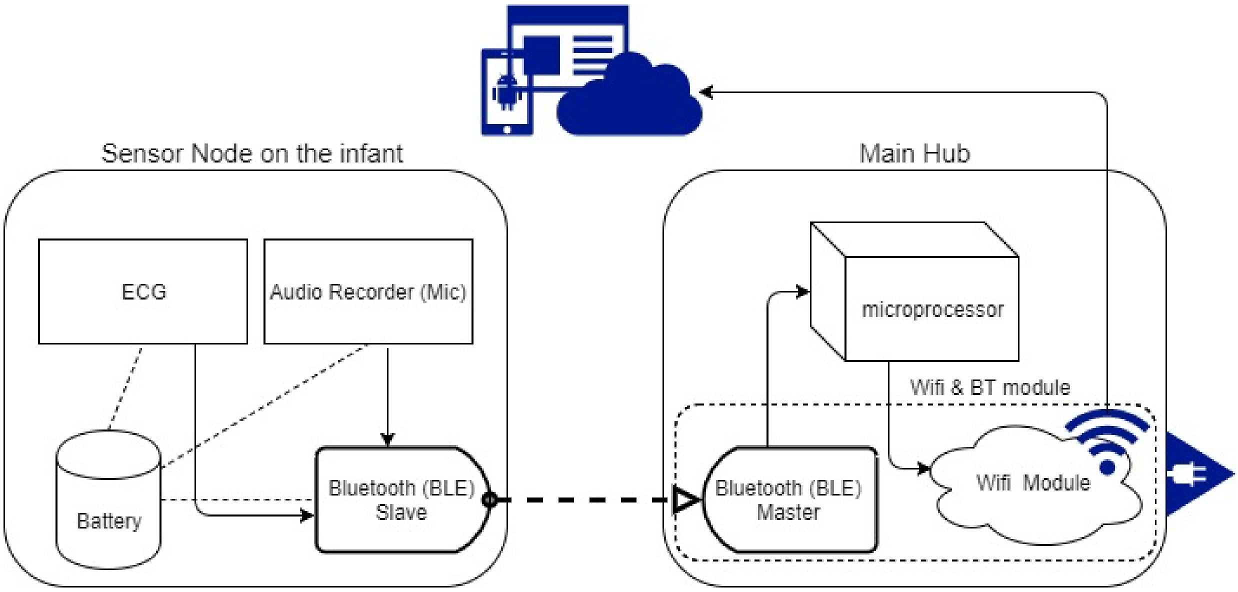

Figure 1: Full System Block Diagram

To allow an infant to move freely within a room or building while also being able to monitor their cardio signals without much obstruction, our design would need to be separated into 2 main parts. One part will have to be worn on the infant to monitor his/her electrocardiogram and record their voice. This part needs to be small, cool (operates with low temperature) and light. Thus, it needs to have minimal hardware, and if there is hardware, it needs to consume low power. So, this part, the Sensor Node as shown in the diagram above, will only have the sensors, the audio recorder, and a low energy Bluetooth module powered by a battery. No data processing will be done on this sensor node, instead, it will directly send the datastream, using Bluetooth, to a main hub. The hub will be the main processing unit. It will contain a Bluetooth module to act as a master, a microprocessor to analyze, filter and sync both the ECG and voice recordings, and a WiFi module to push these data to a cloud server. Since this will be more power hungry, it will be powered by a wall plug. Detailed specifications of each block will be discussed further in the following sections.

2.2 Physical Design

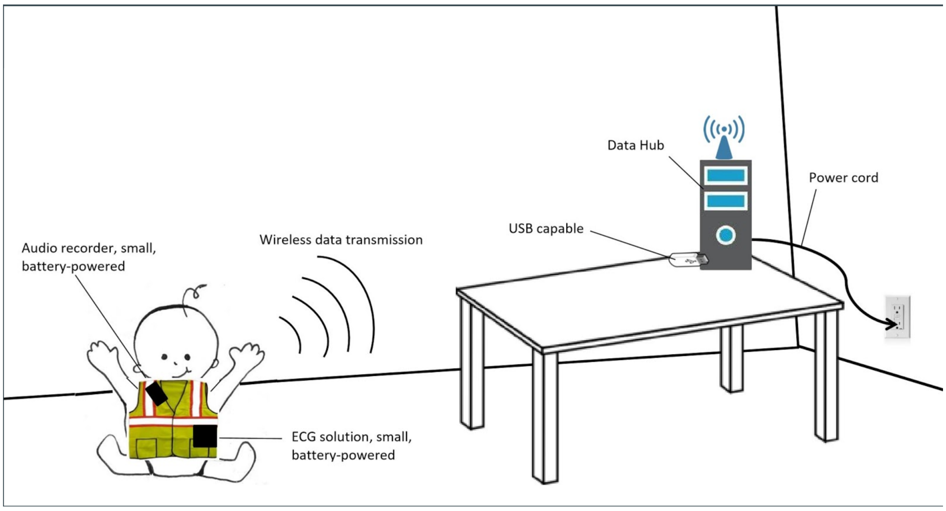

Figure 2: Use Case Scenario of Child Development Sensor System

The diagram above gives a glimpse of what the prototype of our project would look like. The sensor node will be embedded into a vest so that an infant can simply wear the vest on top of their clothing, and all the sensors will be in contact with him/her while also making it difficult for the infant to tamper with the sensors. The vest will be designed by the mechanical team. The vest will be fully battery powered to allow free movement. Since everything is embedded within a vest, it would be more convenient if even the leads of the ECG will be reusable instead of the typical one-time-use disposable electric leads. Hence, when characterizing our ECG sensors, we will also look into non-adhesive leads options.

The sensor node in the vest will send its data to a main hub, which will be stationary (shown as data hub in Figure 2). It will preferably be placed near a WiFi router so that it can push the received data into the cloud smoothly.

2.3 Functional Overview

2.3.1 Sensor Node

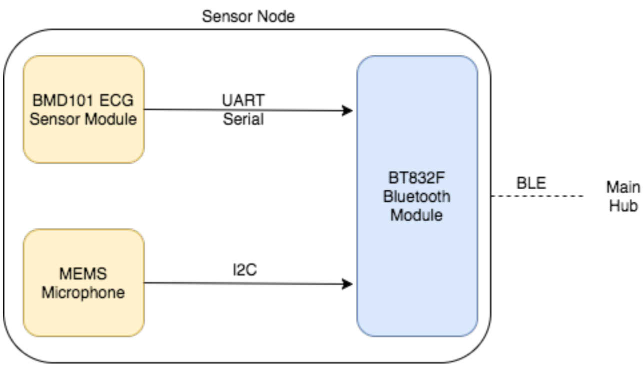

Figure 3: Sensor Node Modular Block Diagram

The Sensor Node shown in Figure 3 is the components that will be attaching to the test subject. This is the main sensing component that will be communicating wirelessly with the data hub through Bluetooth. Subcomponents contained within the sensor node include the ECG sensor, microphone, power electronics, and communication antennas. In Figure 3, we have chosen what we think are the best suitable components/modules.

Firstly, the ECG sensor which will be recording a child's heartbeat as a waveform and not just beats per minutes (bpm). To accomplish the above, we have to decide how many electrodes are necessary or sufficient to graph usable waveforms. Most common ECG lab machines have 12 leads, but this would make our final package too bulky for a toddler to wear. Alternatively, we could use 3 or 5 leads. Lesser electrode contacts result in noisier waveforms and less accurate measurements. We would have to find a sweet spot with the number of electrodes such that the collected data can be considered valid. On top of that, the electrode should be non-adhesive which defers from conventional electrodes that are one-time use adhesive electrodes.

The voice recording aspect is to supplement ECG data such that researchers would know what the infant/toddler was doing during the measurement period. The biggest challenge would be implementing a microphone module that would be sensitive for clear audio recording. Both these sensors will communicate directly through data lines or buses with the Bluetooth module. Given the selected sensor modules, BMD101 ECG module uses a UART Serial output which can then be packaged by the Bluetooth module before transmitting. For the MEMS microphone, since it is digital output, most of these microphones output through an I2C bus. We will most likely use BT832F as our Bluetooth shield solely because it has these two serial I/O protocols.

Block requirements:-

- Overall dimensions of the final PCB with components mounted should fit the dimensions specified by the mechanical engineering team.
- Power consumption should be low enough to keep the temperature of the housing/casing to below 100 Degrees Fahrenheit (37 Degrees Celsius).
- Needs to be light so that it does not affect an infants movements. Sensor node preferably around 2 lbs excluding housing/casing.
- Does not have loose parts that can easily be ingested by an infant or toddler.

2.3.1.1 Sensors

Typical voltage differences throughout our body caused by our heartbeats are in the order of a few hundred microvolts to a few milivolts. Thus, it would be great to have 12 leads on a subject so that all the voltage differences can be added together before amplification. However, given the limitations of our project, we will aim for just 3 leads since the accuracy we are aiming to achieve is only about 70%. This posts some challenges since having lesser leads might increase the signal to noise ratio. For higher resolution, it would be great if we can obtain 16-bit samples which is the industrial standard. The ECG sensor that we are most interested in is the BMD101 because it comes fully fitted with built-in DSP, analog front-end, and pre-written algorithms that will give us raw 16-bit ECG signal output through UART (57600 baud rate) which can then be plotted into a waveform [7]. Also, some forms of BMD101 come with a dedicated Bluetooth submodule which we will use for wireless packet transmission to the main data hub. BMD101 claims to have a noise level of less than 10uV [7].

We are considering two forms of microphones, electret and MEMS. Electret microphones have a typical frequency range of 20Hz-20kHz which is more than sufficient for our needs as we are trying to record voices at most, but an electret microphone might not be sensitive enough such that audio recordings will be clear. On the other hand, MEMS microphones are smaller and more compact in size. Also, they offer better audio reproduction as it is less prone to vibrations compared to electret microphones. Another advantage to MEMS microphones is the fact that they produce digital output instead of analog outputs which make interfacing with microcontrollers much easier. To decide on which microphone, we would have to validate these claims against our requirements to find a suitable match.

Block requirements:-

- ECG sensors will need to be at least 70% accurate relative to the waveform obtained from a typical ECG sensor in a hospital. Or qualitatively, out of the 5 main dips and peaks observable from an ECG waveform, only the R peaks needs to be easily distinguishable from each other.
- Voice recordings need to be sensitive and clear enough such that there is audible speech obtained from the recordings. Preferably, 16-bit mono samples at around 40kHz sampling rate, a signal to noise ratio of about 70dB-A ('A' means weighted at 1kHz signal).
- Voice recordings might invade a user's privacy, so there must be a physical button to allow users to stop the recordings at any time.

2.3.1.2 Wireless Transmission

For the sensor node, the only wireless component would be transmitting data to the main hub. Most off-the-shelf Bluetooth modules come with built in PCB antennas which makes it easier for our design process since it takes up lesser space and we would have one less component to design. Additionally, for ease of development, getting a Bluetooth module with a built in SoC and memory makes all the handshaking processes easier to deal with, and we will also be able to purchase a development board to learn how each Bluetooth module works. Since it is required that the components on the sensor node be low powered, we will only consider the low powered Bluetooth options, namely BLE. A typical BLE only draws 7mA at peak transmission using 3V supply voltage, and while in other states like idle or sleep, it draws even less than 1μA. Preferably, the Bluetooth modules can handle enough range such that an infant wearing it can freely move anywhere in a room or even within the same floors of a building. So, the BLE modules should provide about 30 meters of range. With the emergence of Bluetooth 5 on BLEs recently, it is possible to go up to 200 meters range while consuming low power.

The Bluetooth module we are interested in right now is the BT832F model. It has a built in PCB antenna, ARM processor, on chip memory and a RAM which is very favorable for our needs. It also uses Bluetooth 5 which claims to give us a range of 200-300 meters line of sight while only taking in very low power. During active mode, it uses around 7.5mA at TX +4dBm, which when added with its sensitivity of -96dBm, gives us a 100dBm power rating. From further research, with walls attenuation within buildings, it should give us about 50m of range when using an embedded 2.5GHz transceiver. This model transmits data at the speed of 8Mbps, which is plentiful for us. Therefore, since this is Bluetooth 5 technology, we will also have the option to fourfold the range at the expense of data transmission rate if needed[8].

Block requirements:-

- Bluetooth ranges can reach at least 10 meters so that an infant can at least move freely within a room.

2.3.1.3 Power Electronics

The sensor node will comprise of several components that require the correct power. For our source, we have decided to use AAA batteries, each rated for 1.5V and 25mA (1000 mAh). We have decided this will be suitable to our needs because this provides enough current for approximately 40 hours. There will be design tradeoffs between using two or three batteries. Using two batteries would allow us to save space on our node, giving the product a smaller form factor. Additionally we would be able to connect the two batteries in series to provide us 3V. As we have noted in sections regarding other components, many of our components require 3.3V. Therefore a boost converter must be designed to step the voltage up to the necessary 3.3V from our 3V source. The series connection does not provide us additional current however 25mA is enough for our sensor node to function. Our two AAA battery setup would be able to provide us 75 mW input power. Using three AAA batteries would produce a larger form factor, however, we would need to step down the voltage from 4.5V to 3.3 for our other components. This would give us more input power at 112.5 mW. We will attempt developing this design first due to the inherent stability of a buck compared to a boost. Additionally a voltage regulator may be used in tandem with the developed buck to eliminate output voltage ripple that may occur at high frequencies due to a transient load.

We will be designing the DC-DC converters from scratch for our sensor node. Initially we plan on prototyping with the breadboard and probing the outputs to confirm that the values are the expected inputs to the node components. Our initial design will look similar to a standard buck or boost converter. See Figure 4 for typical circuit schematics.

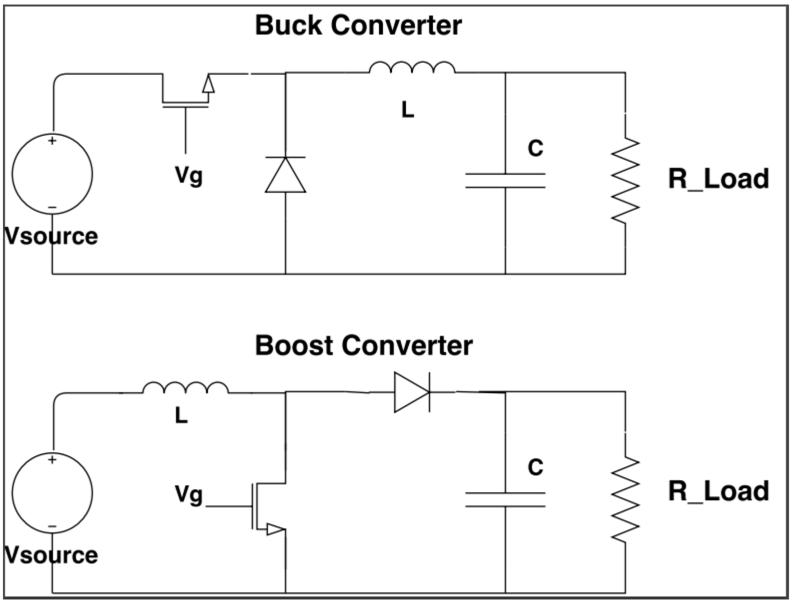

Figure 4: Buck and Boost Converters

To discuss power requirements, we must also discuss maximum load. We will be using the BT832F[8] for our sensor node bluetooth module. The maximum power drawn from this chip is $(7.4mA)(3.6V) = 26.64mW$. For our ECG sensor, BMD101[7], the maximum power draw is $(900\mu A)(3.6V) = 3.24mW$. The microphone, SPH0645LM4H-B, has a maximum draw of $(600\mu A)(3.6V) = 2.16mW$. See 1 for maximum load calculation.

$$\begin{aligned} P_{OUTmax} &= P_{BTmax} + P_{ECGmax} + P_{MICmax} \\ &= 26.64mW + 3.24mW + 2.16mW \\ &= 32.04mW \end{aligned} \tag{1}$$

As seen in the calculation, both the two or three battery designs discussed in this section meets the load power requirements.

Other opportunities to explore would be to design a battery recharging station that is compatible with the sensor nodes. This would heavily increase product lifetime and would eliminate the need to replace old batteries. This would be an addition to the existing baseline that we will be establishing with the battery circuit discussed earlier in this section and a task that will be completed if we have extra time.

Block requirements:-

- Battery has enough capacity to supply power for the whole node for at least 4 hours since this is usually how long an infant will be monitored at one time.

2.3.2 Main Hub

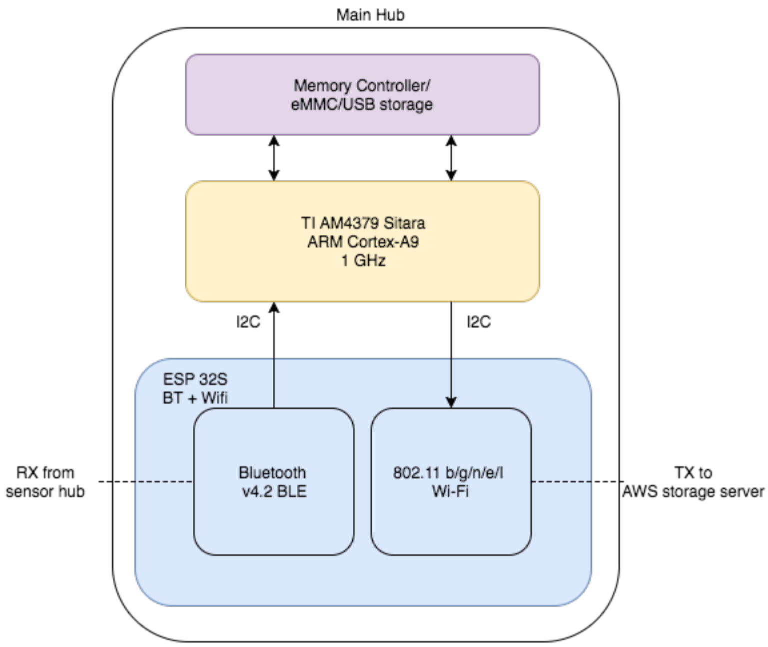

Figure 5: Main Hub Modular Block Diagram

The main hub will be the processing unit of our system. All of the sensor node data will be transmitted across Bluetooth and then processed by the microcontroller before being pushed either to local memory or cloud storage via WiFi. We chose to have most of the high consumption components away from the child to prevent any unwanted harm. Figure 5 shows the modular breakdown of the components in the main hub which consist of a microcontroller, BT + WiFi module, and some form of memory storage. Here we have chosen for each component what we think suits our needs best. A TI Sitara ARM A9 microprocessor, ESP 32S Bluetooth and WiFi combo module. In terms of storage, ideally all collected data points will be pushed to some form of cloud storage, in this case AWS S3. But for debugging and prototyping purposes, local storage will be helpful.

2.3.2.1 Microcontroller

We are considering between a high powered, fully featured microcontroller or a low powered, cost efficient microcontroller. In terms of power draw, it is not a concern since the main hub will be plugged into the wall. So the main factors would be port I/O, developer friendliness, and cost. Below we will list the differences between the 2 microcontrollers one from each category.

On the high end side of the spectrum is the TI AM4379 Sitara with an ARM Cortex-A9 CPU clocked at 1 GHz which might be excessive for our needs. However, the extra processing power can come in handy when multiple sensor nodes are connected to a single main hub. Serial port I/O is not a problem in this case with all of the common protocols, I2C, UART, SPI, and USB.

On the other end of the spectrum is the TI MSP432/MSP430 which has an ARM Cortex-M4 processor clocked at 48 MHz. This is an ultra low powered microcontroller with an active consumption of 80 μA/MHz [10]. One advantage of this particular model is that it has SimpleLink SDK, a widely-used development platform so open source projects are available to reference which might speed up wireless application development.

Block requirements:-

- Since it is important to match voice recordings with the ECG waveform at each time, we must be able to sync the data from the ECG and voice recorder.

2.3.2.2 Wireless Transmission

Figure 6: ESP32 Wifi & BLE module, dimensions: 16mm x 24mm x 3mm

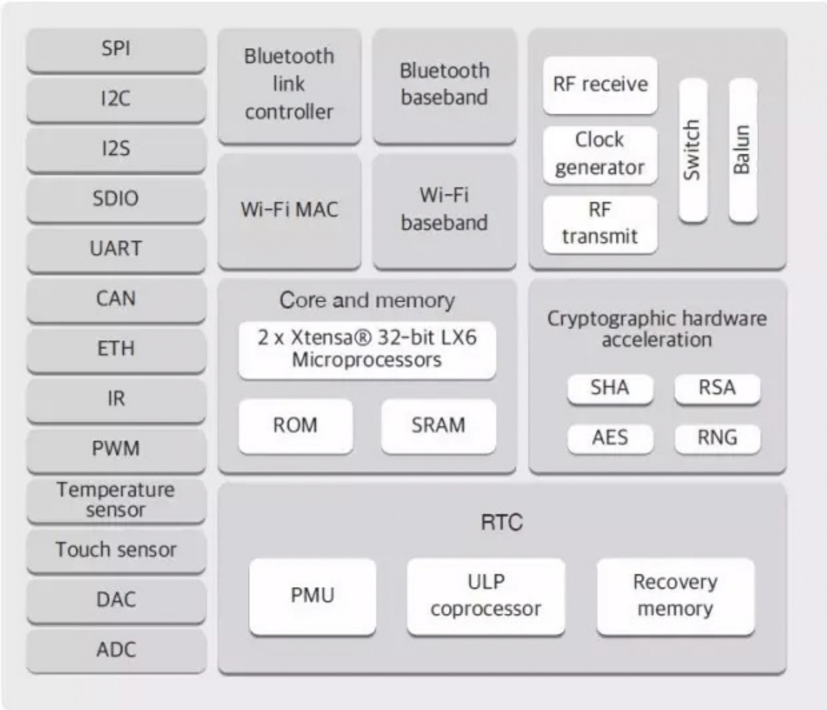

Figure 7: ESP32 Wifi & BLE module features

Bluetooth and WiFi transmission modules are needed. Bluetooth modules are mainly used as a master to receive all the data streams from the sensor node. Since the main hub will be stationary and powered by a wall plug, there is no constraints to the maximum power rating of the Bluetooth module. If there is a need to use a powerful Bluetooth module with large range, for example, if we need to monitor a child's outdoor activity, it is possible to use a powerful Bluetooth module even though it is of a different type as compared to the one on the sensor node. As long as they transmit at the same rate and frequency, we can use a powerful Bluetooth module to extend the communication range.

After receiving all the data, there is a need to push it onto a cloud server so that users can access it anywhere. We will use a WiFi module to achieve this task. A simple 2.4 GHz WiFi module should do the task since it is stationary and it can be placed right beside a router. We will not consider a 5GHz module because it costs more and a typical 80MHz bandwidth is sufficient for our needs. Furthermore, lower frequency offers more range.

The module we are considering now is the ESP32 chip, as shown in Figure 6, which is a compact combination of a Bluetooth and a WiFi module. It features a BLE v4.2 module with about 100m range, an integrated antenna, and a WiFi 2.4 GHz module featuring built in RTC, core memory, security features, and various common protocols like I2C, I2S and UART [11].

Block requirements:-

- Bluetooth module acts as a master and can handle data streams from multiple slaves.
- Allows WiFi to push the data files to cloud servers with minimal delay.

2.3.2.3 Data Back-end

The general idea is to have a software which compiles all the data together with time stamps so that it will be in a readable text file available for playback. Then, this data will be pushed into an AWS S3 storage server. This can be automated by using AWS IoT/Lambda pipelining. AWS IoT helps with the MQTT handshake which is a lightweight messaging protocol optimized for high latency. To further explain, MQTT is a machine-to-machine (M2M)/"Internet of Things" connectivity protocol. It was designed as an extremely lightweight publish/subscribe messaging transport [12].

If we are ahead of our schedule, we might also consider creating a mobile phone application or web-app that can pull selected chunks of data and scrub the timeline. A simple Ionic framework based mobile phone application can be written alongside back-end API calls to AWS. Ionic framework will be used because instead of developing Android or iOS independently, Ionic allows us to develop in HTML/Javascript then port over to either mobile OSes.

Block requirements:-

– Have the data collected compiled and converted into a readable text file available for playback.

– Have the data pushed into an AWS server so that it can be accessed anywhere.

2.3.2.4 Power Electronics

The main data hub will be designed to be a stationary component that will be plugged into a wall outlet. Assuming the product will be used in the United States, the outlet will provide 120 Vrms at 60 Hz. Therefore we must convert the AC voltage to DC for our circuit applications in our hub. The hub will have various components that need DC voltage which include the communication modules for WiFi and Bluetooth and the microcontroller. Once the AC voltage is rectified into a DC voltage, we can then use a DC-DC conversion to step down the voltage to the level our components will be able to use. Another method would be to use a transformer to step down the AC voltage to a lower AC value, and rectify the now lower value to the desired DC value. This would however increase the size of our hub because transformers are relatively large. This is not a big concern because the hub is stationary and should not be moved around. However, this is not a primary concern. A 10:1 transformer would suit our needs, converting 120V AC to 12V AC. Then we would perform rectification to obtain the expected DC values we need. For our components in the hub, around 3.3V is necessary.

To discuss power requirements, we must consider the maximum load power. In our main hub, there are two components: a microprocessor, TI-MSP432[10], and a Bluetooth and Wifi module, ESP32. The maximum power rating for the microprocessor can be calculated as $(100mA)(3.7V) = 0.37W$. The maximum power load for the communication module can be calculated to be $(240mA)(3.6V) = .864W$. See the total load power calculation in 2.

$$\begin{aligned} P_{OUTmax} &= P_{COMmax} + P_{MICROmax} \\ &= .864W + .37W \\ &= 1.234W \end{aligned} \tag{2}$$

Because we are plugged into an outlet, this maximum power load should not be a problem.

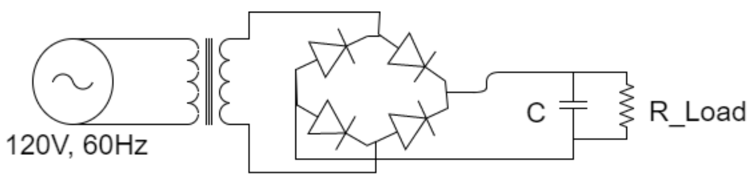

Figure 8: AC-DC Full Wave Rectification

Block requirements:-

– Needs to be able to take in 120V AC wall plug power supply, and convert it to a suitable DC supply for each component of the hub.

2.4 Risk Analysis

There are multiple points of risk to the project. The most predominant would be the accuracy of the ECG data. This is because for research purposes, we would want the ECG to provide accurate enough information for the researchers to use. Inaccurate data would obviously jeopardize the study. Drawing conclusions on faulty data is dangerous to the integrity of the study. Additionally we believe that accuracy of the ECG will be a very tricky task to optimize.

The accuracy of the ECG is dependent on a variety of variables. A variable of concern is the mechanical design of the sensor housing. If this mechanical design does not provide sufficient enough probing capabilities for our electrodes of the ECG, this will cause a big issue with determining ECG waveforms. Another task we need to focus on is the design of the electrodes. One main task that was given to us by the sponsoring professors was that these electrodes must be non-adhesive. This is because it would be tedious to replace electrodes for each use of the device. Therefore we must design the electrode such that we are able to obtain readings even without continuous contact. Most importantly, the predominant variable of concern is the child. This is because children are prone to move around quite often and therefore can easily brush off the electrodes and consequently distort ECG readings. A main task then must be to child-proof the electrode design such that we are able to obtain accurate ECG readings even when the child is in random motion.

Therefore we conclude that the ECG data is the largest risk to our project. This is because ECG data is vital to the research study but can easily be tampered with by the test subject. Therefore we must pay careful consideration to how we design the capturing mechanism for the ECG data.

3 Ethics and Safety

Firstly, the sensor node that will be worn by an infant/toddler has to have safety features implemented into the design which aligns with the IEEE Code of Ethics #1. It states "to accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment." [13] For example, since there will be a battery pack strapped onto the child, overcharging or extreme temperatures can cause overheating or potentially explode. To counter this problem, we will closely monitor battery cell temperatures with a thermistor. Also, over-charging the battery can lead to a breakdown of the cathode, a highly exothermic process. We would have to ensure that our charging circuitry does not go over the threshold voltage.

Since there will be a microphone constantly recording, we have to align with the ACM Code of ethics "Respect the privacy of others." [14] It is our responsibility as engineers to maintain the privacy and integrity of data of other individuals. This includes taking precautions to ensure the accuracy of data, as well as protecting it from unauthorized access or accidental disclosure to inappropriate individuals. [14] To overcome privacy issues, all collected and streamed data will be hardware and software encrypted and only authorized users will be able to decrypt and use said data/information. Most of the briefly mentioned hardware components above do have built-in hardware encryption accelerators and software encryption can be realized by first encrypting each and every packet of data before transmitting. On the server side, encryption will be enabled for each step of the way. Also, all of the wireless communication components comply with the requirements by the FCC.

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